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0. PREFACE

Around 1970 a resurgence of interest about lighter-than-air vehicles (airships) occurred in both the public at large and in certain isolated elements of the aerospace industry. Such renewals of airship enthusiasm are not new and have, in fact, occurred regularly since the days of the Hindenburg and other large rigid airships. However, the interest that developed in the early 1970's has been particularly strong and self-sustaining for a number of good reasons. The first is the rapid increase in fuel prices over the last decade and the common belief (usually true) that airships are the most fuel efficient means of air transportation. Second, a number of new mission needs have arisen, particularly in surveillance and patrol and in vertical heavy-lift, which would seem to be well-suited to airship capabilities. The third reason is the recent proposal of many new and innovative airship concepts. Finally, there is the prospect of adapting to airships the tremendous amount of new aeronautical technology which has been developed in the past few decades thereby obtaining dramatic new airship capabilities.

The primary purpose of this volume is to survey the results of studies, conducted over the last 15 years, to assess missions and vehicle concepts for modern propelled lighter-than-air vehicles.

1. INTRODUCTION

1.1 General

Several workshops and studies in the early 1970's, sponsored by the National Aeronautics and Space Administration and others, (Refs. 1.1-1.19), arrived at positive conclusions regarding modern airships and largely verified the potential of airships for operationally and economically satisfying many current mission needs. Noteworthy among more recent airship activities has been the series of Conferences on Lighter-Than-Air-Systems Technology sponsored by the American Institute of Aeronautics and Astronautics. The 1979 Conference is reviewed in Refs. 1.20 and 1.21. Based on the positive early study conclusions, several organizations have analyzed specific airship concepts in greater detail and, in a few cases, have initiated development of flight test and demonstration vehicles. It is the purpose of this volume to survey the results of these activities.

It will be useful in later discussions to have a clear understanding of the definitions of various types of airships and how they are related (Fig. 1). A lighter-than-air craft (LTA) is an airborne vehicle that obtains all or part of its lift from the displacement of air by a lighter gas. LTA's are conveniently divided into airships (synonymous with dirigibles) and balloons, the former being distinguished by their capability for controlled flight. Only airships are considered here. In Fig. 1, the term "conventional" applies to the class of approximately ellipsoidal fully-buoyant airships developed in the past. It is traditional to classify conventional airships according to their structural concept (rigid, nonrigid, or semirigid). Hybrid airships are herein classified according to the means by which the aerodynamic or propulsive portion of the lift is generated. Hybrid airship is a term which is used to describe a vehicle that generates only a fraction of its total lift from buoyancy, the remainder being generated aerodynamically or by the propulsion system or both.

1.2 Historical Overview

The distinguishing characteristics of the two major conventional airship concepts--rigid and nonrigid--will be discussed briefly. The third type, semirigid, is essentially a variant of the nonrigid type, differing only in the addition of a rigid keel. Specific hybrid concepts will be discussed in detail in subsequent chapters.

A typical nonrigid airship (Fig. 1.2) consists of a flexible envelope, usually fabric, filled with lifting gas and slightly pressurized. Internal air compartments (called ballonets) expand and contract to maintain the pressure in the envelope as atmospheric pressure and temperature vary, as well as to maintain longitudinal trim. Ballonet volume is controlled by ducted air from the propwash or by electric blowers. The weights of the car structure, propulsion system, and other concentrated loads are supported by catenary systems attached to the envelope.

The other major type of airship was classified rigid because of its rigid structure (Fig. 1.3). This structure was usually an aluminum ring-and-girder frame. An outer covering was attached to the frame to provide a suitable aerodynamic surface. Several gas cells were arrayed longitudinally with the frame. These cells were free to expand and contract, thereby allowing for pressure and temperature variations. Thus, despite their nearly identical outward appearance, rigid and nonrigid airships were significantly different in their construction and operation.

The principal development trends of the three types of conventional airships are depicted in Fig. 1.4. The nonrigid airships are historically significant for two reasons. First, a nonrigid airship was the first aircraft of any type to achieve controllable flight, nearly 125 years ago. Second, nonrigid airships were the last type to be used on an extensive operational basis; the U.S. Navy decommissioned the last of its nonrigid airship fleet in the early 1960's. During the many years the Navy operated nonrigid airships, a high degree of availability and reliability was achieved. Most of these nonrigid airships were built by Goodyear and a few, based on a modified Navy design, are used today for advertising by that company.

The rigid airship was developed primarily by the Zeppelin Company of Germany and, in fact, rigid airships became known as Zeppelins. Even the small percentage of rigid airships not built by this company were based, for the most part, on Zeppelin designs. The rigid airships of the Zeppelin Company recorded some historic "firsts" in air transportation, including inaugurating the first scheduled air service. The culmination of Zeppelin development was the Graf Zeppelin and Hindenburg airships--

unquestionably outstanding engineering achievements for their day. All of the rigid airships produced in the United States were for military purposes; none were in operation at the outbreak of World War II.

An historical question of interest concerning modern airship developments is "Why, after years of operation, did lighter-than-air vehicles vanish from the scene?" There is considerable confusion on this point; the reasons are, in fact, different for each of the formerly established airship uses.

There were basically two military missions for which large rigid airships were developed. The first was their use by Germany as aerial bombers in World War I. They were never very effective in this role and by the end of the War, due to their altitude and speed limitations and the improving capabilities of fixed wing aircraft and ground artillery, they had become vulnerable and obsolete. The other military development of rigid airships was by the U.S. Navy in the late 1920's and early 1930's. In this application, the airship served as a carrier of fixed wing aircraft which provided surveillance for surface fleets. This concept was demonstrated to be operationally successful, although it was never proven in wartime. The end of this development was a direct result of the wreck of both airships, the Akron and the Macon, which had been built for this purpose.

The only significant past commercial airship operations were those of the Zeppelin Company and its subsidiary DELAG. The highlights of these operations are listed on Table 1.1. None of these commercial operations can be considered a financial success and most were heavily subsidized by the German government. For example, the transatlantic service with the Graf Zeppelin in 1933-1937 required a break-even load factor of 93-98%, a value seldom achieved, despite carrying postage at rates over ten times higher than 1975 air mail rates.

Throughout most of these commercial operations, there was little or no competition from heavier-than-air craft. However, airplane technology was making rapid strides and airplane speed, range, and productivity were rising steadily. Airships and airplanes are difficult to compare because of the remoteness of the time period and the limited operational experience. Nevertheless, by the time of the Hindenburg disaster in 1937, it seems clear that the most advanced airplane, the DC-3, had lower operating costs as well as higher cruising speeds than the most advanced airship, the Hindenburg (Refs. 1.22 and 1.23). Of course, this tended to be offset by the Hindenburg's luxury and longer range. Nevertheless, it is clear that although the burning of the Hindenburg hastened the end of the commercial airship era, it was not the primary cause; the airship had become economically uncompetitive.

By all accounts, the use of nonrigid airships by the U.S. Navy in World War II and subsequent years was very successful. The Navy's fleet of nonrigids increased from 10 vehicles at the beginning of the War to 165 at the end, and over 500,000 flight hours were logged during the War. The airships were used for ocean patrol and surveillance, primarily as related to surface vessel escort and antisubmarine operations. The decommissioning of the Navy's airship fleet in 1961 was due apparently to austere peacetime military budgets and not to any operational deficiency.

1.3 State-of-the-Art Assessment

We will conclude this Introduction with a discussion of the technical, operational and economic characteristics of past airships and indicate how modern technology could be used to improve the performance of all airship designs.

All three types of conventional airships evolved into a common shape, the familiar "cigar shape" with circular cross sections and a nearly elliptical profile. The fineness ratio of the later rigid airships was typically in the range 6-8. The fineness ratio of the nonrigid airships, which tended to be smaller and slower than the rigid ones, was typically in the range 4-5.

It is generally acknowledged today that past conventional, fully buoyant airship designs were very nearly optimum for this class of vehicle in terms of aerodynamic shape and fineness ratio. Thus a modern conventional airship could not be expected to show much improvement in this regard. It is estimated that a drag reduction of approximately 10% would be possible with adequate attention to surface smoothness. Use of boundary-layer control may give significantly greater drag reduction (Ref. 1.24). Reviews of airship aerodynamics for both conventional and hybrid configurations may be found in Refs. 1.25 and 1.26. Also of interest for aerodynamic analysis is Ref. 1.27.

The early airships were designed primarily by empirical methods, and the only company to accumulate sufficient experience to design successful rigid airships was the Zeppelin Company. Two areas in which there was a serious lack of knowledge were aerodynamic loads and design criteria. Work in these areas was continued after the decommissioning of the last rigid airship in expectation of further developments. Significant progress was made in both analytical and experimental techniques, but further work would need to be done in these areas for a modern airship.

The frames of most of the past rigid airships consisted of built-up rings and longitudinal girders stabilized with wire bracing. The rings and longitudinals were typically made of aluminum alloy and the bracing was steel. This structure was very light and efficient, even by present standards. However, this construction was highly complex and labor intensive, and any modern airship of this type would have to have a much simpler construction. Possibilities include the use of metalclad monocoque, sandwich, or geodesic frame construction. Materials would be modern aluminum alloys or filamentary composite materials. A good candidate for wire bracing, if required, is Kevlar rope. It is estimated that the use of modern construction and materials would result in a hull weight saving of approximately 25% compared with a past design such as the Macon.

There have been dramatic improvements in softgoods with applications for airships in the past two decades. Softgoods are used for gas cells and outer coverings for rigid airships and for envelopes for nonrigid airships. The material most often used in past airships for these applications was neoprene-coated cotton, although the envelopes of the later nonrigid airships were of dacron. The dramatic improvement in strength of modern softgoods compared with cotton is shown in Fig. 1.5. Kevlar appears to be the best material, but it has not been fully developed for use in large airships. It is estimated that use of modern softgoods would result in component weight reductions of 40-70% compared with past designs. Coating films also have been improved greatly, which will result in a tenfold improvement in gas cell and envelope permeability.

With a few explainable exceptions, past airships have all had about the same structural efficiency (as measured by empty weight/gas-volume ratio) despite differences in size, design concept, year of development, and lifting gas. The insensitivity to size is a reflection of the airship "cube-cube law" (i.e., both the lifting capability and the structural weight increase in proportion to the cube of the principal dimension for a constant shape). Since fixed-wing heavier-than-air craft follow a "square-cube law," airships will compare more favorably with heavier-than-air craft as size is increased. Smaller airships have tended to have nonrigid or semirigid construction, whereas the larger airships have been rigid, and this would be true of modern vehicles as well.

Either Otto- or Diesel-cycle engines were used on the large airships of the 1930's. The internal combustion engine has lower fuel consumption in small sizes; however, the turbine engine can be adapted for a variety of fuels and is lighter and quieter. As compared with engines of the 1930's, modern engines have about 90% of the specific fuel consumption and as low as 10% of the specific weight and volume. Perhaps more important than these improvements is the greatly improved reliability and maintainability of modern turboshaft engines. Thrustors will be either prop/rotors or ducted fans; ducted fans are quieter, safer for ground personnel, and have higher thrust.

There are also some longer-term alternative propulsion systems for airships. The Diesel engine is attractive because of its low fuel consumption. However, no Diesel currently available is suitable for airship use. Another possible propulsion system is a nuclear powerplant, particularly for long endurance missions and large airships. An extensive development program will be required to develop a nuclear-powered airship.

Engine controls of the rigid airships consisted of an engine telegraph that transmitted engine control commands from the helmsman to an engine mechanic, who would then manually make the required engine control changes. Modern electronic power management systems will eliminate this cumbersome system and greatly increase the responsiveness, accuracy, and reliability of engine controls. Control of the thrust vector orientation by tilting mechanisms will also be greatly enhanced with modern systems.

Flight-control systems on past airships have been largely mechanical. Commands from the helm (one each for vertical and horizontal surfaces) were transmitted by cable and pulley systems to the control surfaces. In addition, there were manual controls for releasing ballast and valving lifting gas. For a large modern airship, a fly-by-wire or fly-by-light control system has obvious advantages and would likely be employed. This system would use many airplane- and/or helicopter-type components. An autopilot would also be provided.

Between the 1930's and the present, there has been a vast improvement in avionics systems due largely to the dramatic changes in electronic communications devices. For example, as compared with 1930 components, modern aviation radio equipment is about one-tenth the size and weight and is much more versatile and reliable. Progress in the development of electronic components has also made possible the introduction of many navigation devices not available in the 1930's (e.g., VOR/DME/ILS, TACAN, radar, LORAN, OMEGA, and inertial systems).

The various improvements in controls, avionics, and instrumentation will only modestly reduce the empty weight of the airship, but will significantly improve its controllability and reliability. Of course, a large increase in acquisition cost will be associated with these modern systems and components, but this will be offset by lower operating costs due to manpower reductions.

The operation of the 1930's airships was as labor intensive as their construction. In flight, large onboard crews were required to constantly monitor and adjust the trim of the ship and maintain nearly neutral buoyancy. Trim and neutral buoyancy were maintained by one or more of the following procedures: valving lifting gas, dropping ballast, transferring fuel or other materials within the airship, collecting water from the atmosphere and engine exhaust, and moving crew members within the airship. Also, it was not unusual to repair the structure and the engines in flight. It is obvious that modern structural concepts, engines, avionics, control systems, and instrumentation will decrease the workload of the onboard crew considerably.

The experience of the U.S. Navy in the 1940's and 1950's with nonrigid airships indicates that modern airships can be designed to have all-weather capability at least equivalent to that of modern airplanes. High winds and other inclement weather need not endanger the safety of the airship and its crew either in flight or on the ground. However, high adverse winds will continue to have a negative impact on the operational capability of airships due to their low airspeeds.

Extremely large ground crews were needed to handle the early Zeppelins. These airships were walked in and out of their storage sheds by manpower. Up to 700 men were used to handle the Zeppelin military airships. The first significant change was the development of the high-mast mooring system by the British. The U.S. Navy then developed the low-mast system, which was more convenient, less expensive, and allowed the airship to be unattended while moored.

Important developments in ground handling subsequent to the 1930's were made by the Navy in connection with its nonrigid airship operations. By 1960, the largest nonrigid airships were routinely being handled on the ground by small crews that used mobile masts and "mules." These mules were highly maneuverable tractors with constant-tension winches. Some further improvement in ground-handling procedures would be possible with a modern airship. Handling "heavy" or hybrid airships would be particularly easy.

As shown in Fig. 1.6, the flyaway costs per pound of empty weight of the rigid airships of the 1930's were comparable with those of transport airplanes of the same era. Since then, the costs of transport airplanes have steadily risen, even when inflationary effects are factored out, because the steady introduction of new technology has made succeeding generations of airplanes more sophisticated and expensive. The increased costs have paid off in increased safety, reliability, and productivity. As discussed above, a modern airship would have several systems and components that are highly advanced compared with 1930's technology. Thus it seems likely that rigid-airship flyaway costs would follow the trend of fixed wing aircraft (Fig. 1.6), and therefore a modern rigid airship should cost about the same as an equivalent weight modern airplane. A modern nonrigid airship could cost somewhat less.

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Airship	Year	Main Route	Number of Flights	Flight Hours	Total Distance, nm	Number of Passengers	Mail lb	Freight lb
7 Airships (Delag)	1910-1914	Pleasure Flying	1,588	3,176	93,000	35,028	--	--
LZ-120 Bodensee & Nordstern	1919	Friedrichshafen --Berlin	103	532	27,650	2,253	11,000	6,600
LZ-127 Graf-Zeppelin	1933-1937	Friedrichshafen --Rio De Janeiro	590	17,177	914,000	13,110	86,200	67,000
LZ-129 Hindenburg	1936-1937	Friedrichshafen --Lakehurst	63	3,088	182,000	3,059	19,550	21,450
Total			2,617	23,973	1,220,964	56,040	116,750	95,050

Table 1.1 Past commercial airship operations

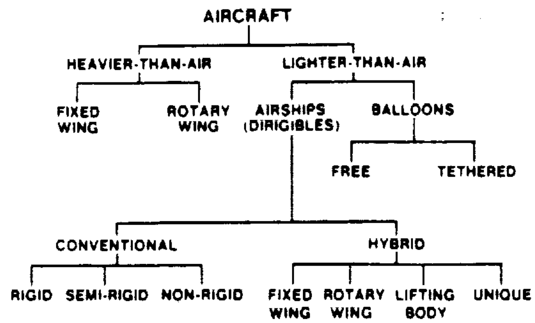

Fig. 1.1 Classification of aircraft

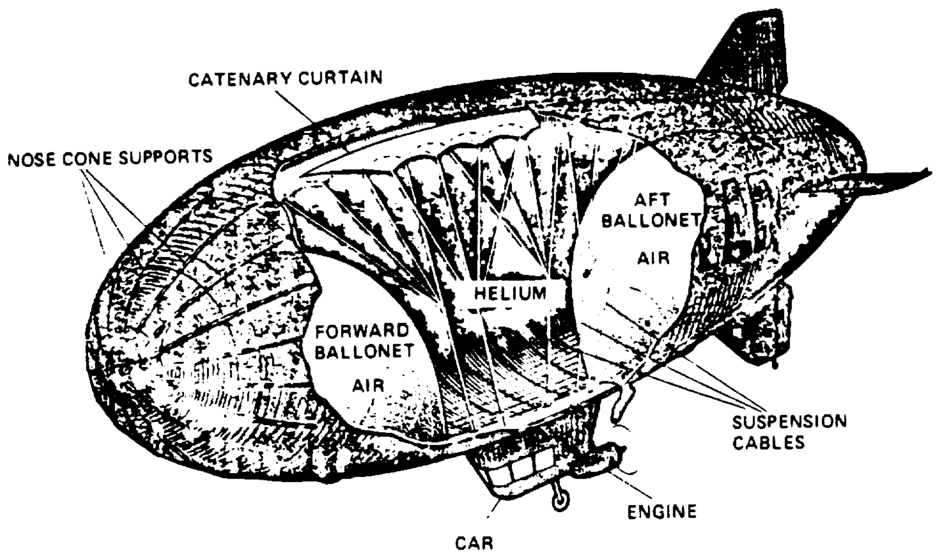

Fig. 1.2 Typical nonrigid airship

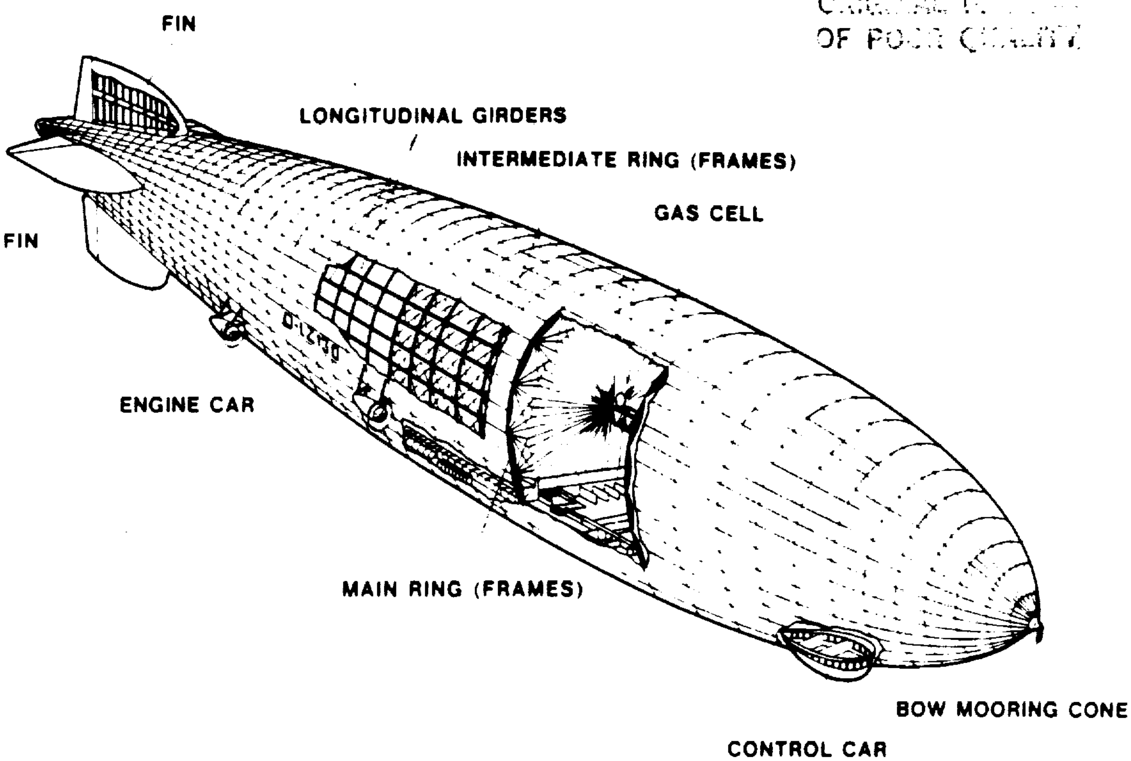

Fig. 1.3 Typical rigid airship

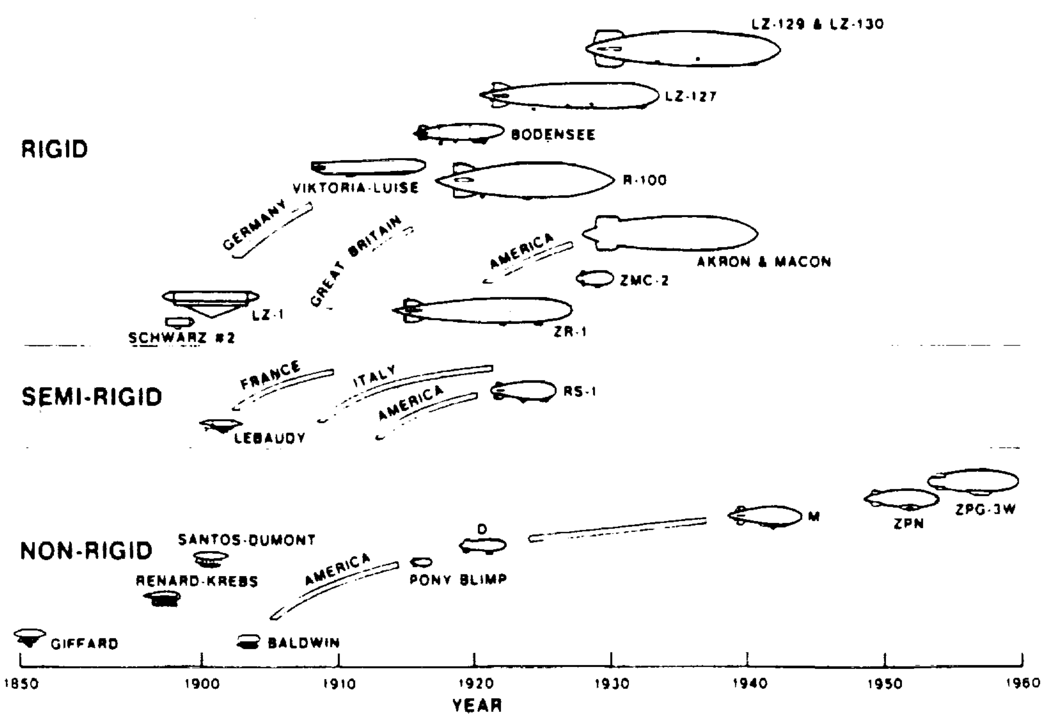

Fig. 1.4 History of airship development

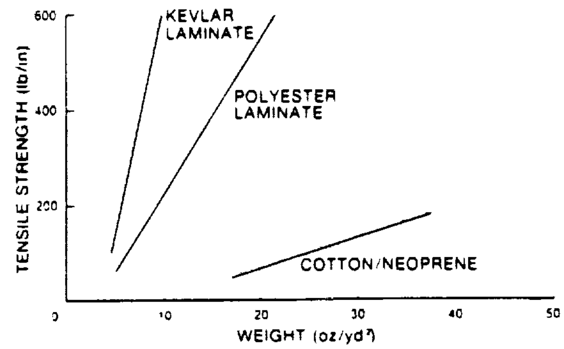

Fig. 1.5 Softgoods tensile strength

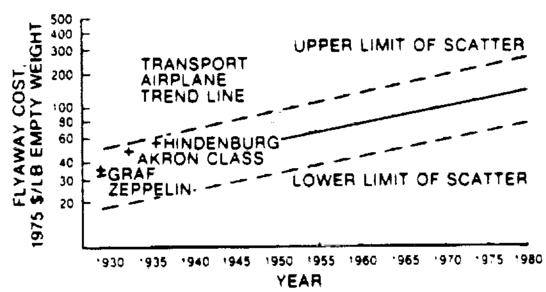

Fig. 1.6 Historical trend of flyaway costs

2. PATROL AND SURVEILLANCE

2.1 Mission Characteristics and Vehicle Requirements

It was mentioned in the Introduction that the most successful past employment of airships was their use for ocean patrol and surveillance by the U.S. Navy during World War II and subsequent years. For two major reasons, there has been recently a sharp rekindling of interest in improving patrol and surveillance capability, particularly over water. First, the rapidly increasing sophistication and numbers of Soviet combat ships, particularly submarines, have increased the need for deep ocean surveillance platforms (with high endurance and high dash speeds) capable of employing a wide variety of electronic and acoustic devices. Second, the recent extension of territorial water limits to 200 miles offshore has greatly increased the need for coastal patrols for a wide variety of maritime tasks.

Missions similar to coastal patrol and deep ocean surveillance, in terms of vehicle design requirements, are disaster relief and law enforcement.

It is not difficult to see why airships are being considered for this class of mission. Relative to conventional surface ships, the airship has greater dash speed, is not affected by adverse sea conditions, and has a better observational vantage point. It is less detectable by underwater forces, more visually observable to surface vessels and other aircraft, and can be made less visible to radar. Relative to other types of aircraft, the airship has the ability to station-keep with low fuel expenditure (and thus has longer endurance), can deliver a substantial payload over long distances, and has relatively low noise and vibration. In effect, the airship as a vehicle class can be thought of as filling the gap between heavier-than-air craft and surface vessels in terms of both speed and endurance (Fig. 2.1) and speed and payload (Fig. 2.2). These figures are for coastal patrol platforms but the same could be said for deep ocean surveillance vehicles as well. In the final analysis, perhaps the biggest stimulus for the renewed interest in airships for these missions is the present high cost of petroleum-based fuels.

Thus there are many fundamental reasons why the airship enjoyed success in its past patrol and surveillance role with the Navy and why there is considerable interest in this application for the future. In fact, many recent studies have arrived at positive conclusions for using airships for these missions (Refs. 2.1-2.6). However, it must be kept in mind that the airship is not the panacea for all patrol and surveillance applications. For situations in which either sustained or exceptionally high dash speed is crucial, or high altitude is highly desirable, or the transfer of large amounts of material to another vessel is required, or hostile forces are present, another vehicle type would likely be superior. An airship enjoys its high endurance and payload performance only at low speed and altitudes. High dash speed is possible, but requires high fuel consumption; therefore, performance will be poor unless dash speed is used only sparingly. Payload capability falls off rapidly as altitude increases and, additionally, fuel consumption increases for station-keeping because of higher relative winds at higher altitudes.

In view of the premium on endurance in most patrol and surveillance missions, a fully or nearly fully buoyant airship of classical nearly ellipsoidal shape is indicated, and most recent studies have considered only this basic vehicle type (Refs. 2.3, 2.5, and 2.7). Because of the dramatic improvement in softgoods over the last few decades, mentioned in the previous section, attention has been focused on the nonrigid concept. Using modern materials, nonrigid airships are now probably superior to rigid designs at least up to a size of 5×10^6 ft^3 and possibly well beyond. The two major variables affecting vehicle design for the various patrol and surveillance missions are vehicle size (driven primarily by payload and endurance requirements) and degree of "hoverability" required.

It must be mentioned that several operational issues remain at least partly unresolved for airships performing the missions under consideration here. Many of these questions will likely be resolved only by operational experience with actual vehicles. One of these issues is weather. By the very nature of most patrol and surveillance tasks, any vehicle must be able to operate in an extremely wide variety of weather conditions. Operational locations cover the entire globe and thus climates range from arctic to tropical. Missions must be performed in all weather and in fact for some applications, such as rescue work, operational requirements increase as weather conditions deteriorate. The Navy's experience with airships in the 1940's and 1950's indicates that airships can be designed to have the same all-weather performance as other aircraft. Even though some doubts still remain, modern design methods should be able to improve even further the ability of airships to operate in heavy weather.

Another question is that of low speed control. The classical fully-buoyant large airship, having only aerodynamic controls, was largely uncontrollable at airspeeds below 15 knots (Ref. 2.7). This would be operationally unacceptable for most patrol and surveillance missions. This was also a primary cause of the ground handling problems experienced by past airship operations. It is clear that a low speed control system, probably utilizing propulsive forces, will be required.

The question of how to ground-handle airships would seem to be the major unresolved issue. Past airship operations were characterized by large manpower requirements, large ground facilities, and frequent damage to the vehicles. Although the U.S. Navy made considerable improvements in its nonrigid airship operations towards the end, there is still a definite need for improvement. An essential requirement would seem to be the development of an all-weather, outdoor mooring system with minimal ground crew requirements. Addition of a low speed control system to the vehicle should help considerably.

Finally, assuming all operational questions have been satisfactorily resolved, the development of airships for patrol and surveillance will hinge on their cost effectiveness in performing these tasks. Most of these applications can be done by other existing and proposed vehicle types and therefore a careful comparative economic analysis will be required.

2.2 Coastal Patrol

In the past few years there has been a great deal of interest in the use of airships by the U.S. Coast Guard. This stems primarily from the extension of the limits of territorial waters to 200 miles offshore and the dramatic increase in fuel prices over the last 10 years. The U.S. Coast Guard and the U.S. Navy, with support from NASA, have conducted and sponsored numerous studies of the application of airships to various Coast Guard missions (Refs. 2.1-2.3, 2.7, 2.8). A study of the use of airships in Canada is reported in Ref. 2.9. Almost without exception, these studies have concluded that airships would be both cost effective and fuel efficient when compared with existing and planned Coast Guard aircraft for many coastal patrol tasks.

To quote Ref. 2.8: "The predominant need within Coast Guard mission areas is for a cost effective aerial surveillance platform. The object of surveillance may be an oil slick, an individual in the water, an iceburg or pack ice, small craft, fishing vessel or even a submersible. [In all these cases] the need exists for the mission platform to search, detect, and identify or examine. Consequently any airship design for Coast Guard applications must consider the capability to use a variety of sensors operating throughout the electromagnetic spectrum. Undoubtedly, the primary long range sensor for most missions will be some form of radar. It would also be desirable for such a platform to be able to directly interact with the surface--to deploy and retrieve a small boat; to tow small craft, oil spill cleanup devices, and sensors; and to deliver bulky, moderate weight payloads to the scene of pollution incidents. If an airship were capable of routinely directly interacting with the surface, such an airship could serve as a very effective multimission platform. However, the airship must serve predominately as a fuel efficient aerial surveillance platform."

With these basic requirements in mind, a recent study (Refs. 2.2, 2.3) identified eight Coast Guard tasks for which airships seem to be potentially suitable. The characteristics and requirements of these tasks are listed in Table 2.1. The maximum capability required for each mission parameter is underlined. At the present time, the Coast Guard uses a mix of boats, ships, helicopters, and fixed-wing aircraft to perform these tasks. However, many typical mission profiles for the applications listed in Table 2.1 seem to be better tailored to the airship's natural attributes, in that endurance is of prime importance and high speed dash and precision hover occur only infrequently and for relatively short duration (Ref. 2.1).

To summarize airship vehicle mission requirements, in Ref. 2.8 it is concluded that the following qualities are needed: (1) Endurance of 1 to 4 days, depending on cruise speed; (2) dash speed of 90 knots; (3) fuel efficient operation at speeds of 20 to 50 knots; (4) controllability and hoverability in winds from 0 to 45 knots; (5) ability to operate in almost all climates and weather conditions; and (6) ability to survive, both on the ground and in the air, in all weather conditions.

Two recent industry studies (Refs. 2.10 and 2.11) have conceptually designed airships to meet the mission requirements listed in Table 2.1. The size of airship required ranges from a volume of about 300×10^3 ft^3 for the Port Safety and Security (PSS) mission to about 1000×10^3 ft^3 for the Marine Science Activities (MSA) mission. All studies concluded that an airship of about 800×10^3 volume and 2000 horsepower could perform every mission except MSA, and could even do that mission with a somewhat reduced capability. The specifications and performance of a typical conceptual design are indicated in Table 2.2 (Refs. 2.7, 2.10). As stated in Ref. 2.7, such a vehicle would employ modern but proven technology and be well within the size range of past successful nonrigid designs. Therefore, the technical risk would be low.

The most significant difference in the design of a modern coastal patrol nonrigid airship, as compared with past Navy vehicles, will be the use of propulsive lift to achieve low speed controllability and hoverability. In fact, the power requirements and the number and placement of propulsors is likely to be determined from hoverability requirements rather than from cruise performance. Such a vehicle would also be capable of vertical takeoff and landing (VTOL) performance although increased payloads would be possible in short takeoff and landing (STOL) operation.

Two different approaches to a modern coastal patrol airship are shown in Figs. 2.3 and 2.4 (Refs. 2.3, 2.10-2.12). The trirotor Goodyear design (the characteristics of which are listed in Table 2.2) mounts two tilting propellors forward on the hull and the third at the stern. Movable surfaces, on an inverted V-tail supporting the stern propeller and on the wings supporting the forward propellers, provide forces and moments in hover. A notable advantage of this concept is the greater cruise efficiency of the stern propeller, resulting from operating in the airship's wake. The quadrotor Bell design is an adaptation of the Piasecki Heli-stat, or buoyant quadrotor concept, under consideration for vertical heavy lift and described in Section 2.2. In the quadrotor approach, two diagonally opposed rotors carry a steady down load while the other two produce an upward force. By this means, rotor lift forces are available for cyclic deflection to produce control forces and moments. A significant feature of this concept is that no ballast recovery would be necessary.

A preliminary study of the acquisition and operating costs of the type of maritime patrol airship just described has been undertaken (Refs. 2.2, 2.3). Briefly, this study arrived at a unit cost of about $5 million per airship (based on a production of 50 units). When the required investment in ground facilities and training is factored in, the total initial investment cost rises to $6.4 million per airship. The life-cycle costs, when prorated on a flight hour basis, were estimated to range between $750 to $1150 per flight hour, depending on the mission. These costs are very competitive with those of existing mission-capable aircraft and surface vessels, and a preliminary survey of Coast Guard needs identified a potential requirement for more than 75 airships. The study concluded that airships appear to be technically and operationally feasible, cost-effective, and fuel-efficient for many maritime patrol needs.

The remaining unresolved technical issues for a coastal patrol airship all have to deal with hoverability. The following questions all need more precise answers than are available today: What is the degree of hoverability required for mission effectiveness? What is the best design concept for a hoverable airship? What is the trade-off between performance in cruise and in hover?

A major step toward answering these questions is being taken in the current flight tests of the AI 500 (Skyship) by the U.S. Coast Guard and U.S. Navy. The AI 500 is a development of Airship Industries of the United Kingdom. It is a nonrigid airship of 181,000 ft^3 volume and has many advanced design features such as composite material structures and vectored thrust propulsion. In addition to the maritime patrol flight demonstrations in the U.S., the airship is being tested in England for the purpose of obtaining an airworthiness certificate (Ref. 2.13) for commercial and military use.

2.3 Deep Ocean Patrol

As mentioned previously, there is increasing concern over the growing threat of Soviet seapower and this has led to a renewed interest in airships for patrol and surveillance at locations far removed from the shore. As compared to the coastal patrol missions, modern airships for deep ocean missions have been analyzed in only a very preliminary way. Since the biggest threat seems to be from submarines, we will concentrate here on the anti-submarine warfare (ASW) class of missions, but applications to sea control escort, electronic warfare, and oceanography (the latter largely a civil application) will be considered briefly as well. The principal references for the discussion which follows are Refs. 2.4-2.6, and particularly Ref. 2.4, which focuses on the ASW mission.

According to a quote in Ref. 2.4, "The Soviet submarine force continues to be a primary threat to our vital sea lanes of communications and to our naval forces during an armed conflict." A basic mission need thus exists "...to provide the Navy with an affordable, improved ASW capability to counter a growing submarine threat to our merchant ships, projection forces, and ballistic missile firing submarines." Compounding the problem is the fact that the oceans are getting "noisier," due to increased activity from ships, weapons, and counter measures, at the same time that advancing technology is rendering submarines "quieter." ASW was a key element of the Navy's efforts in World War II (Ref. 2.14) and it is clear that, if anything, it will be even more important in the future.

Basically, in ASW an area of the ocean must be patrolled in a given period of time to detect, classify, locate, and either trail or attack the submarines found. This requires placing a vehicle in the required location and providing it with the sensors and weapons necessary to perform these duties. There is really no one "ASW mission" but rather a wide variety of tasks. Among the mission parameters which will affect vehicle design and performance are: distance to the operating area, time on station, response time, extent of the area to be searched, and the functions to be performed. Because of the complex nature of ASW, the U.S. Navy currently depends upon a variety of air and surface platforms and sensors used in a coordinated manner. An airship, if developed for this purpose, would work in conjunction with other vehicle types, doing only those aspects of ASW for which it is best suited.

It must be mentioned that the airship is by no means the only "advanced concept" being considered for ASW and related Navy applications. Figure 2.5 shows several possible advanced vehicle concepts including the surface effect ship (SES), the small water area twin hull (SWATH) ship, the patrol hydrofoil, the sea-loiter aircraft, the advanced land-based maritime patrol aircraft, and the helicopter and other V/STOL aircraft. Preliminary conclusions regarding many of these concepts have been positive. The recent Advanced Naval Vehicles Concept Evaluation Program has been the most detailed comparative study of these vehicle concepts to-date (Ref. 2.15). Since not all, if any, of these concepts can be developed by the Navy in the near future, much careful vehicle analysis remains to be done.

Reference 2.4 has provided a preliminary analysis of the principal features of a deep ocean patrol airship. It would be a conventionally shaped airship of about 4×10^6 ft^3 volume, provided that refueling at sea is done routinely (but probably considerably larger if required to be completely self-sufficient). It should have a maximum speed of at least 85 knots and a service ceiling of at least 10,000 ft. The crew size would be approximately 15-18 people and, with refueling and resupply done at sea, the airship should be able to stay on station almost indefinitely. It is obvious that such a platform would be attractive for many ASW tasks. One of its outstanding attributes is the airship's capability for carrying ASW sensors. Reference 2.4 concludes that an airship can use almost all of the existing and proposed sensors, although some may require slight modification. As compared to existing sensor platforms, the airship provides a unique combination of high payload, large size, low vibration, long-term station-keeping ability, and low noise propagated into the water. It would be particularly effective in towing large acoustic arrays.

On the negative side, airships may have some disadvantages with regards to offensive combat capability and vulnerability to both weapons and weather. The question of all-weather capability for airships was discussed in Section 2.2, where it was conjectured that this will not be more of a problem than for other vehicles. The question of vulnerability to weapons is perhaps also not as serious a problem as it would first appear. It is true that an airship would be in most respects the most visible of all possible ASW platforms. However, the radar cross section could probably be made to be no larger than that of fixed-wing aircraft because it should be possible to make the envelope transparent to radar. An airship vehicle may be no more vulnerable to weapons than any other platform because impact to the envelope would not be generally lethal. The suitability of an airship as a weapons platform remains to be resolved.

Most ships and aircraft in use by any navy are multifunctional by necessity, and an airship, as any new vehicle, would be expected to be likewise. There appear to be several other missions for which an airship designed primarily for ASW could provide support; these include anti-surface warfare, anti-air warfare, airborne early warning, electronic warfare, mine warfare, logistics resupply, and oceanography. Many of the airship's natural attributes could be used to advantage in these missions. One interesting possibility is that the airship could be designed for maximal, instead of minimal, radar cross section and could be used to simulate a carrier task group. It would also be an excellent platform for electronic support measures.

The potential of airships for sea control and task force escort missions has been examined in Ref. 2.5. The basic problem is to protect a task force from long-range anti-ship cruise missiles, requiring over-the-horizon detection. This function is now performed by carrier-based aircraft but they are not well suited for this purpose and their use in this role decreases the task force offensive capability. The role of the airship would be to provide standoff airborne early warning (AEW) as well as command and control for counter attack systems. Reference 2.5 estimates that the use of airships in this way would increase the cost-effectiveness and striking power of the carrier task force, primarily by freeing heavier-than-air craft for other missions.

An aspect of the AEW mission which is not well suited to airships is the need for high altitude in order to attain as large a radar horizon as possible. In Ref. 2.5 an operating altitude of 15,000 ft is proposed as a good compromise between airship size and radar horizon. At this altitude, for a payload requirement of 60,000 lb, a 7×10^6 ft^3 vehicle is required. Thus, although the AEW airship could perform many ASW tasks, a vehicle designed for ASW would be too small and would have insufficient altitude capability for most AEW tasks.

One final deep ocean mission which deserves mention is oceanography. Although this application is too limited ever to justify airship vehicle development on its own, if a deep ocean naval airship were ever developed such a vehicle would have many interesting civil and military oceanographic applications (Ref. 2.6). Basically, airships could make ocean measurements that are difficult, or impossible, to make from existing platforms. For example, an improved ability to conduct remote sensing experiments of both the sea surface and the lower marine atmosphere are badly needed. The airship would work in conjunction with existing satellite systems and oceanographic ships.

To conclude this section, we paraphrase the conclusion in Ref. 2.4. Lighter-than-air vehicles seem to be a viable vehicle choice for many ASW missions and other deep ocean missions. Their unique features give them many advantages over surface vessels and other aircraft for these applications. An ocean patrol airship would have multimission capability and would work well in concert with existing vehicles. Development of such a vehicle would require minimal new vehicle technology and would not require the development of new sensor and other systems.

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	Enforcement of Laws and Treaties	Marine Environmental Protection	Military Operation/ Preparedness	Port Safety and Security	Search and Rescue	Short Range Aids to Navigation	Marine Science Activities	Ice Operations
	ELT	MEP	MO/MP	PSS	SAR	A/N	MSA	IO
	Surveillance, Interdiction and Seizure of Illicit Fishing and Drug Traffic	Search and Surveillance of the Marine Environment; Assist in the Logistics and Command, Communication, and Control of Clean Up Operations	Surveillance for Enemy Forces; Anti-submarine Warfare; Protection of Offshore Installations; Convoy Ships; Logistics Support; Inshore Undersea Warfare	Hazardous Cargo Traffic Control; Command, Control and Communications	Search, Logistics and Aid	Monitor Buoys	Ice Patrol; Oceanographic Survey; Locating Buoys	Surveillance of Ice Conditions
Duration, h	27.5	12.5	26.5	8.35	13.6	17.0	35.5	20.5
Total payload, lb	7,669	22,372	10,929	6,237	7,910	7,396	7,761	7,482
Cruise speed, knots	50	50	40	40	60	50	60	60
Dash speed, knots	90	--	90	--	90	--	--	--
Crew (200 lb each)	11	6	11	6	8	8	--	--
Maximum altitude, ft	5,000	5,000	5,000	5,000	5,000	1,000	5,000	5,000
Tow	--	--	Sonar	--	Ship	--	--	--

Table 2.1 Potential maritime patrol airship missions

Envelope Volume, ft^3	875,000
Length, ft	324
Diameter, ft	73
Gross Weight, lb	60,664
Empty Weight, lb	38,160
Useful Load, lb	22,504
Static Lift, lb	52,164
Dynamic Lift, lb	8,500
Buoyancy Ratio	0.86
Horsepower Required	2,400
Maximum Altitude, ft	5,000
Maximum Speed, knots	97
Range at 50 knots, n. mi.	3,290
Endurance at 25 knots, hr	101

Table 2.2 Goodyear Aerospace ZP-3G specifications and performance

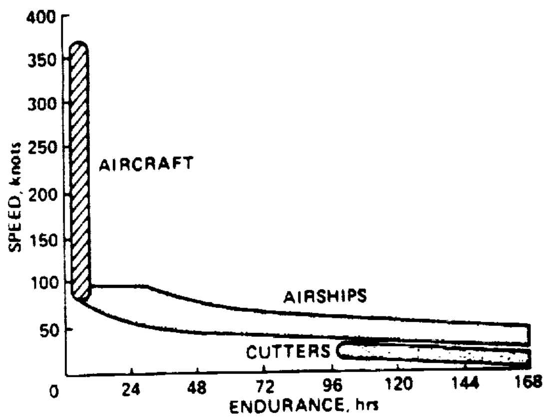

Fig. 2.1 Vehicle speed and endurance

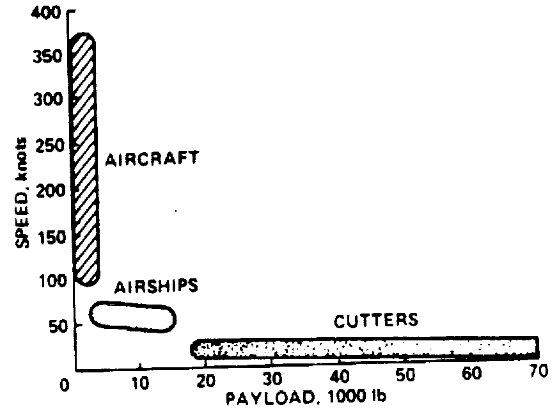

Fig. 2.2 Vehicle speed and payload

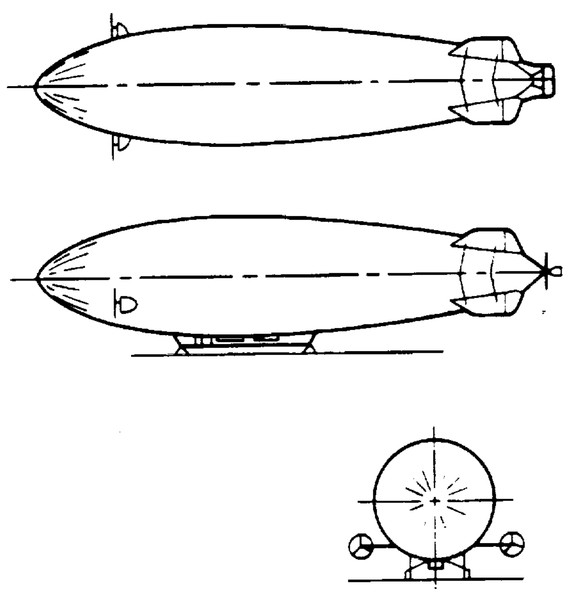

Fig. 2.3 Goodyear Aerospace patrol airship design

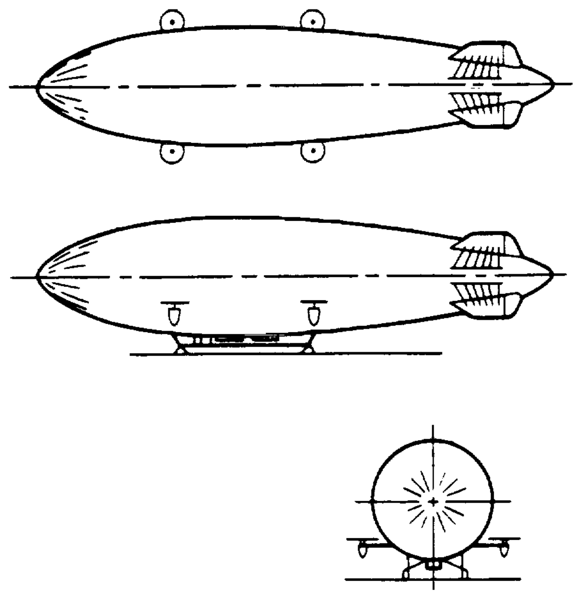

Fig. 2.4 Bell Aerospace patrol airship design

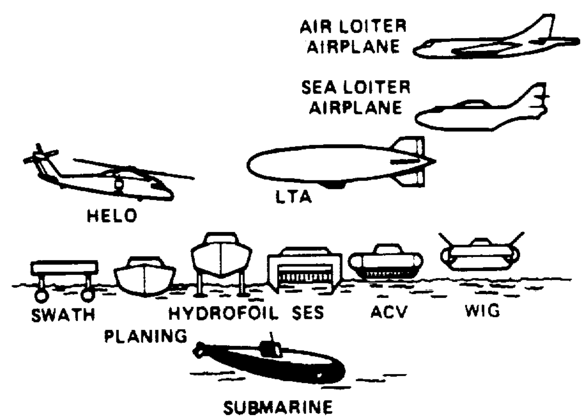

Fig. 2.5 Advanced Naval vehicle concepts

3. VERTICAL HEAVY-LIFT

3.1 Mission Characteristics and Market Analysis

Early studies (Refs. 1.1-1.18 and 3.1-3.9) concluded that modern air-buoyant vehicles could satisfy the need for vertical lift and transport of heavy or out-sized payloads over short distances.

There are two reasons that such aircraft, called heavy-lift airships (HLAs), appear attractive for both military and civil heavy-lift applications. First, buoyant lift does not lead to inherent limitations on payload capacity as does dynamic lift. This is because buoyant-lift aircraft follow a "cube-cube" growth law whereas dynamic-lift aircraft follow a "square-cube" law, as discussed in Section 1.3.

Figure 3.1 shows the history of rotorcraft vertical-lift capability. Current maximum payload of free world helicopters is about 18 tons. Listed in the figure are several payload candidates for airborne vertical lift that are beyond this 18-ton payload weight limit, indicating a market for increased lift capability. Noteworthy military payloads beyond the existing vertical-lift capability are the main battle tank and large seaborne containers. Extension of rotorcraft lift to a 35-ton payload is possible with existing technology (Refs. 3.10, 3.11), and future development of conventional rotorcraft up to a 75-ton payload appears feasible (Ref. 3.11). With HLA concepts, however, payload capability of up to 200 tons is possible using existing propulsion-system technology or even, if desired, existing rotorcraft propulsion-system hardware.

The second reason airships appear attractive for heavy lift is cost. Most HLA concepts are projected to offer lower development, manufacturing, maintenance, and fuel costs than large rotorcraft with the same payloads; thus total operating and life-cycle costs may be lower. The lower development cost arises from extensive use of existing propulsion-system technology or hardware, or both, making major new propulsion-system development unnecessary. Low manufacturing and maintenance costs accrue because buoyant-lift components are less expensive to produce and maintain then dynamic-lift concepts. Lower fuel costs follow directly from lower fuel consumption. As fuel prices increase, the high fuel efficiency of HLAs will become increasingly important. HLA costs and fuel efficiency will be discussed in more detail later.

Because the market for vertical lift of payloads in excess of 20 tons is a new one for aerial vehicles, the size and characteristics of the market are somewhat uncertain. As a result, several studies have been undertaken. Many of these studies have been privately funded and their results are proprietary, but the results of some have been published (Refs. 3.8, 3.9, 3.12-3.15). HLA market-study conclusions have been generally favorable. Table 3.1 summarizes the results of one of these, the NASA-sponsored study of civil markets for HLAs (Refs. 3.12, 3.13).

The HLA civil market tends to fall into two categories. The first consists of services that are now or could be performed by helicopters, but perhaps only on a very limited basis. Payloads are low to moderate, ranging from about 15 to 80 tons. Specific markets include logging, containership offloading (of interest also to the military), transmission tower erection, and support of remote drill rigs. HLAs would be able to capture greater shares of these markets than helicopters because of their projected lower operating costs. Most of these applications are relatively sensitive to cost. The largest market in terms of the potential number of vehicles required is logging.

The second HLA market category involves heavy payloads of 180 to 800 tons--a totally new application of vertical aerial lift. This market is concerned primarily with support of heavy construction projects, especially power-generating plant construction. The availability of vertical aerial lift in this payload range will make the expensive infrastructure associated with surface movements of heavy or bulky items largely unnecessary. It would also allow more freedom in the selection of plant sites by eliminating the restrictions imposed by the necessity for readily accessible heavy surface transportation. Further, it could substantially reduce construction costs of complex assemblies by allowing more extensive pre-assembly in manufacturing areas. This application is relatively insensitive to cost of service. There would be military as well as civil application of ultraheavy lift.

The classical fully-buoyant airship is unsuitable for most vertical heavy-lift applications because of poor low-speed control and ground-handling characteristics. Therefore, almost all HLA concepts that have been proposed are of the "hybrid" type. Because buoyant lift can be scaled up to large sizes at low cost per pound of lift (as previously described), it is advantageous from a cost standpoint in hybrid aircraft to provide as much of the total lift as possible by buoyancy. The fraction of total lift derived by dynamic or propulsive forces is determined primarily by the amount of control power required. The dynamic forces, therefore, provide propulsion and control as well as a portion of the total lift.

The characteristics of hybrid aircraft and their potential for the heavy-lift mission were first clearly recognized by Piasecki (Refs. 1.12, 3.3), by Nichols (Ref. 3.2), and by Nichols and Doolittle (Ref. 3.6). References 3.2 and 3.6, in particular, describe a wide variety of possible hybrid HLA concepts. In the following sections, specific hybrid airship concepts for heavy-lift applications will be discussed.

3.2 Buoyant Quad-Rotor Concept

A heavy-lift airship concept which has received a great deal of attention is the buoyant quad-rotor (BQR) which combines helicopter engine/rotor systems with airship hulls. This basic idea is not new. In the 1920's and 1930's a French engineer, E. Oehmichen, not only conceived this idea, but successfully built and flight-tested such aircraft, which he called the Helicostat (Ref. 3.8). One of his first designs (Fig. 3.2a) had two rotors driven by a single engine mounted beneath a cylindrical buoyant hull. According to Ref. 3.8, Oemichen's purpose in adding the buoyant hull to the rotor system was threefold: "...to provide the helicopter with perfect stability, to reduce the load on the lift-rotors, and to slow down descent with optimum efficiency."

Oehmichen's later effort was a quad-rotor design with two rotors mounted in the vertical plane and two in the horizontal (Fig. 3.2b). The hull was changed to an aerodynamic shape more characteristic of classical airships. Existing motion pictures of successful flights of the Helicostat demonstrate that the BQR concept was proven feasible in the 1930's.

The modern form of the concept was first proposed by Piasecki (Refs. 1.12, 3.3). Piasecki's idea is to combine existing, somewhat modified, helicopters with a buoyant hull as exemplified in Figure 3.3. The configuration shown in Figure 3.3 will be called the "original" BQR concept. The attraction of the idea lies in its minimal development cost. In particular, no new major propulsion-system components would be needed (propulsion systems are historically the most expensive part of an all-new aircraft development). A fly-by-wire master control system would command the conventional controls within each helicopter to provide for lift augmentation, propulsive thrust, and control power.

Other variants of the BQR idea are currently under study. A design by Goodyear Aerospace (Ref. 3.16) is shown in Figure 3.4. As compared with the original concept (Fig. 3.3), this design (called the "advanced" concept) has a new propulsion system, auxiliary horizontal-thrusting propellers, and aerodynamic tail surfaces and controls. The four propulsion system modules would make extensive use of existing rotor-craft components and technology but would be designed specifically for the BQR. The horizontal-thrusting propellers would be shaft-driven from the main rotor engines. These propulsion modules would be designed more for high reliability and low maintenance costs, and less for low empty weight, than are typical helicopter propulsion systems. They would be "derated" relative to current systems, leading to further reductions in maintenance costs.

In a revival of the Helicostat concept, a buoyant dual-rotor HLA has been studied by Aerospatiale (Ref. 3.8). It would use the engines and rotors from a small helicopter, but propellers would be fitted for forward propulsion and yaw control (Fig. 3.5). Payload would be about 4 tons; the principal application is envisioned to be logging.

The performance capability of the BQR design (Fig. 3.3) was examined in the feasibility studies of Refs. 1.12-1.14 and 1.16 and is listed in Table 3.2 This design employs four CH54B helicopters, somewhat modified, and a nonrigid envelope of 2.5×10^6 ft^3. Total gross weight with one engine inoperative is about 325,000 lb., of which 150,000 lb. is payload. Empty-to-gross weight fraction is 0.455 and design cruise speed is 60 knots. Range with maximum payload is estimated to be 100 n. mi.; with the payload replaced by auxiliary fuel, the unrefueled ferry range would be more than 1,000 n. mi.

In References 1.12, 1.16, and 3.3, the ratio of buoyant-to-total lift (β) is chosen so that the vehicle is slightly "heavy" when completely unloaded. In effect, the buoyant lift supports the vehicle empty weight, leaving the rotor lift to support the useful load (payload and fuel). A different approach has been suggested and studied by Bell et al. (Ref. 3.17). Bell et al. proposed that β be selected so that the buoyancy supports the empty weight plus half the useful load. It is then necessary for the rotors to thrust downward when the vehicle is empty with the same magnitude that they must thrust upward when the vehicle is fully loaded. This same principle has been used in the studies of the rotor-balloon, discussed in the following section. Use of the approach suggested by Bell et al. (high β), as opposed to the approach assumed in Table 2.4 (low β), has the potential of offering lower operating costs since buoyant lift is less expensive than rotor lift. Also, the Bell approach has better control when lightly loaded, because higher rotor forces are available. In comparison, the low β approach may result in a vehicle that is easier to handle on the ground (since it is heavy when empty) and one that is more efficient in cruise or ferry when lightly loaded or with no payload (because of low rotor forces). Selection of the best value of β depends on these and many other factors and will require a better technical knowledge of the concept.

The BQR vehicle will be effficient in both cruise and hover compared with conventional-design heavy-lift helicopters (HLH). This arises primarily from the cost advantages of buoyant lift when compared with lift on a per-unit-of-lift basis, as discussed earlier. Fuel consumption of the BQR vehicle in hover will be approximately one-half that of an equivalent HLH. Relative fuel consumption of the BQR in cruise may be even lower because of the possibility of generating dynamic lift on the hull, thereby reducing or eliminating the need for rotor lift in cruising flight.

When cruising with a slung payload, the cruising speeds of HLH and BQR vehicles will be approximately the same since external load is generally the limiting factor on maximum speed. When cruising without a payload, as in a ferry mission, the speed of the BQR will be lower than that of an HLH. The many HLA studies have shown, however, that the higher efficiency of the BQR more than offsets this speed disadvantage. Therefore, the BQR should have appreciably lower operating costs per ton-mile in either the loaded or unloaded condition.

Total operating costs per ton of payload per mile in cruise flight are compared in Fig. 3.6 (based on data provided by Goodyear). The figure shows that the advanced BQR concept offers a decrease in operating costs by as much as a factor of 3 compared with existing helicopters. Of course, much of this cost advantage results from the larger payload of the BQR (approximately eight times larger). Operating costs in cruise flight of the advanced concept are lower compared with those of the original concept. This arises from the use of propellers instead of rotor cyclic pitch for forward propulsion, from lower assumed propulsion maintenance costs, and from lower drag due to a more streamlined interconnecting structure. The advanced concept BQR would be particularly efficient when cruising lightly loaded (as in ferry), since it would operate essentially as a classical fully-buoyant airship.

Studies have shown that precision hover and station-keeping abilities approaching those of proposed HLHs are possible with BQR designs (Refs. 1.12, 3.3, 3.18-3.20). Automated precision hover systems recently developed for an HLH (Ref. 3.10) can be adapted for BQR use. Recent studies of BQR dynamics and control are reported in Refs. 3.21-3.24.

In a program funded by the U.S. Forest Service and managed by the U.S. Navy, Piasecki Aircraft Corporation is currently assembling a demonstration vehicle of the BQR type. The flight vehicle will combine four H-34 helicopters with a 1,000,000 ft^3 nonrigid envelope. It will have a 25-ton payload and will be used to demonstrate aerial logging.

3.3 Rotating Concepts

An early hybrid HLA concept, which has subsequently received a significant amount of study and some initial development, is a rotor-balloon configuration (called Aerocrane by its inventors, the All American Engineering Company). Early discussions of this concept appear in References 3.1, 3.2, 3.5-3.7; two versions of the Aerocrane are depicted in Fig. 3.7. The original configuration consisted of a spherical helium-inflated balloon with four rotors (airfoils) mounted at the equator. Propulsors and aerodynamic control surfaces were mounted on the rotors. The entire structure (except the crew cabin and payload support, which were kept stationary by a retrograde drive system) rotated (typically at a rate of 10 rpm) to provide dynamic rotor lift and control. Principal applications envisioned for the rotor-balloon are logging and containership offloading.

Study and technology development of the rotor-balloon concept have been pursued by All American Engineering and others, partly under U.S. Navy sponsorship. Emphasis of the program has been on devising a suitable control system. A remotely controlled flying model was built to investigate stability, control, and flying qualities (Fig. 3-8). Results (Refs. 3.25-3.27) have shown that the rotor-balloon is controllable and that it promises to be a vehicle with a relatively low empty-to-gross weight ratio and low acquisition cost across a wide range of vehicle sizes. Technical issues that emerged were (1) the magnitude and effect of the Magnus force on a large rotating sphere and (2) the high acceleration environment (about 6 g in most designs) of the propulsors.

Although the rotor-balloon technical issues are thought to be solvable, two characteristics emerged as being operationally limiting. First, large vehicle tilt angles were required to obtain the necessary control forces in some operating conditions. Second, the high drag associated with the spherical shape resulted in very low cruise speeds, typically 25 mph for a 16-ton payload vehicle. This low speed meant that operation in winds of over 20 mph probably was not possible and that the efficiency of operation in even light winds was significantly degraded. Even with no wind, the low speed resulted in low productivity. Thus, the original rotor-balloon concept was limited to very short-range applications in very light winds.

The advanced configuration rotor-balloon depicted in Figure 3.7 (Ref. 3.28) is designed to overcome the operational shortcomings of the original concept. Winglets with aerodynamic control systems are fitted to allow generation of large lateral-control forces, thereby alleviating the need to tilt the vehicle. A lenticular shape is used for the lifting gas envelope to decrease the aerodynamic drag. The increase in cruise speed of the advanced concept is, however, accompanied by some increase in design complexity and structural weight.

A more substantial departure from the original Aerocrane concept has been proposed recently. The Cyclo-Crane (Refs. 3.29, 3.30) is essentially a new HLA configuration concept (Fig. 3.9). It consists of an ellipsoidal lifting gas envelope with four strut-mounted airfoils at the midsection. The propulsors are also located on these struts. This entire structure rotates about the longitudinal axis of the envelope to provide control forces during hover. Isolated from the rotating structure by bearings are the control cabin at the nose and the aerodynamic surfaces at the tail. The payload is supported by a sling attached to the nose and tail. The rotation speed and yaw angles of the wings on their struts are controlled to keep the airspeed over the wings at a constant value; namely, a value equal to the vehicle cruise speed. Thus, for hover in still air, the wingspan axes are aligned with the envelope longitudinal axis. As forward speed is increased, the vehicle rotational speed decreases and the wings are yawed until, at cruise speed, the rotation is stopped and the wingspan axes are perpendicular to the forward velocity. Hence, in cruising flight the Cyclo-Crane acts as a winged airship.

Preliminary analysis of the Cyclo-Crane has indicated that a cruising speed of 670 mph would be possible with a 16-ton payload vehicle and that the economic performance would be favorable (Ref. 3.31). The Aerolift Company is currently building a Cyclo-Crane flight demonstration vehicle at Tillamook, Oregon. It is scheduled to be flight tested in logging operations in 1985.

Another recent rotating hybrid airship concept under development is the LTA 20-1 of the Magnus Aerospace Corporation (Refs. 3.32, 3.33). The configuration consists of a spinning helium-filled spherical envelope and a ring-wing type gondola (Fig. 3.10). The combination of buoyancy, Magnus lift, and vectored thrust result in a vehicle with controllable heavy-lift capability.

3.4 Other Concepts

Perhaps the simplest and least expensive of the HLA concepts are those which combine the buoyant- and dynamic-lift elements in discrete fashion without major modification. Examples, taken from References 1.7 and 3.6, are shown in Figure 3.11. Although such systems will obviously require minimal development of new hardware, there may be serious operational problems associated with them. Safety and controllability considerations would likely restrict operation to fair weather. Further, cruise speeds would be extremely low. The concept from Ref. 3.6 that is shown in Figure 3.11 was rejected by the authors of Ref. 3.6 because of the catastrophic failure which would result from an inadvertent balloon deflation.

Another approach to heavy lift with buoyant forces is the clustering of several small buoyant elements. Examples of this are the ONERA concept (Ref. 1.7) and the Grumman concept (Ref. 3.34) shown in Fig. 3.12. In the Grumman idea, three airships of approximately conventional design, such as the one shown, are used to lift moderate payloads. When heavy lift is needed, the three vehicles are lashed together temporarily while in the air. The technique for joining the vehicles and the controllability of the combined system need further study.

Finally, another HLA concept that has received some attention is the "ducted-fan hybrid" shown in Fig. 3.13 (Ref. 3.6). In this vehicle, a toroidal-shaped lifting gas envelope provides a duct or shroud for a centrally located fan or rotor. There has been too little study of the ducted-fan hybrid, however, to permit an assessment of its potential.

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Market area	Useful load, tons	Number of vehicles required
Heavy-lift		
Logging	25-75	> 1000
Unloading cargo in congested ports	16-80	200
High-voltage transmission tower erection	13-25	10
Support of remote drill-rig installations	25-150	15
Ultraheavy-lift		
Support of power-generating plant construction	180-900	30
Support of oil-gas offshore platform construction	500	3
Other transportation	25-800	10

Table 3.1 Principal heavy-lift airship markets

Gross weight,[a] lb	324,950
Rotor lift, lb	180,800
Buoyant lift, lb	144,150
Empty weight, lb	148,070
Useful load,[a] lb	176,800
Payload, lb	150,000
Static heaviness,[a] lb	3,920
Envelope volume, ft^3	2.5×10^6
Ballonet volume, ft^3	5.75×10^5
Ballonet ceiling, ft	3,500
Hull fineness ratio	3.2
Design speed (TAS), knots	60
Design range	
With maximum payload, n. mi.	100
No payload, n. mi.	196
Ferry, n. mi.	1,150

[a]Sea level, standard day, 93% inflation, one engine out, reserves for 100 ft/min climb.

Table 3.2 Weight statement and performance of 75-ton buoyant quad-rotor, original concept

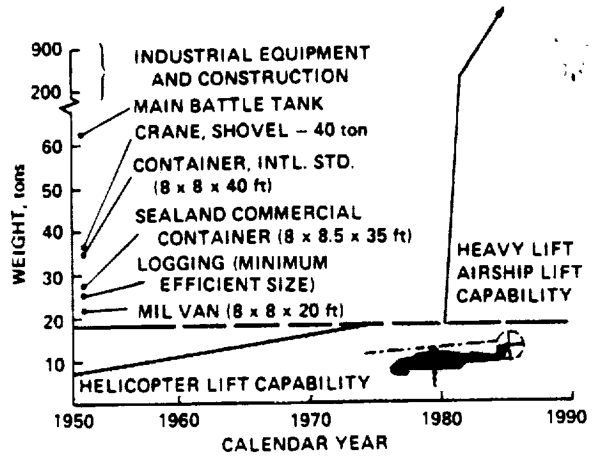
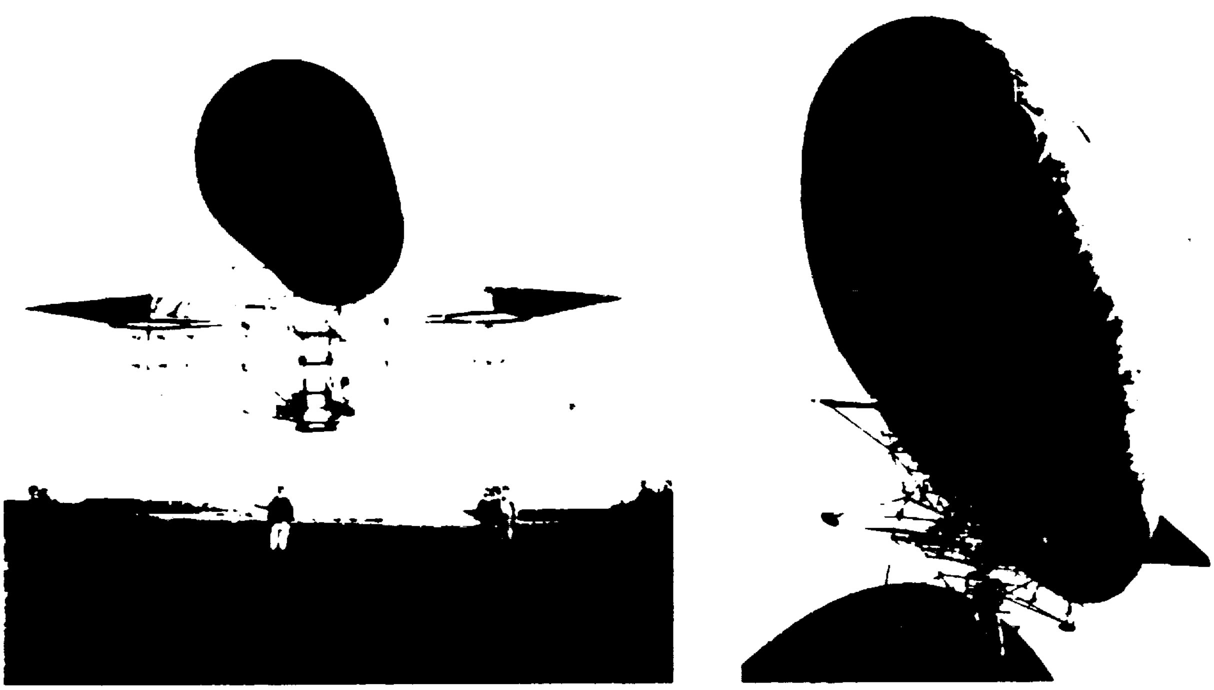


Fig. 3.1 Potential heavy-lift payloads



(a) (b)

Fig. 3.2 Oehmichen's Helicostat flight vehicles

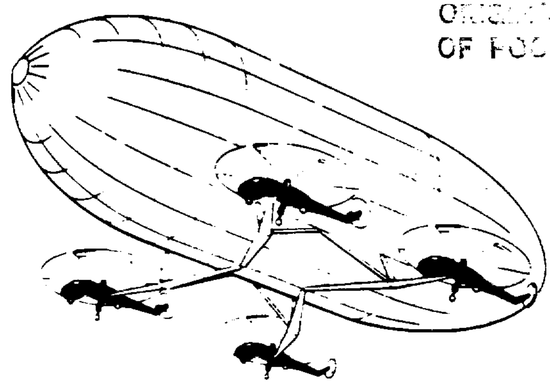


Fig. 3.3 Buoyant quad-rotor, original concept (Heli-Stat)

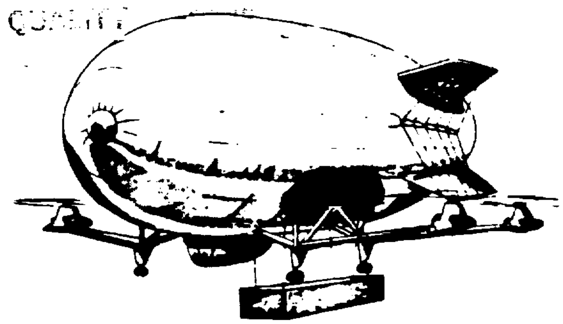


Fig. 3.4 Buoyant quad-rotor, advanced concept

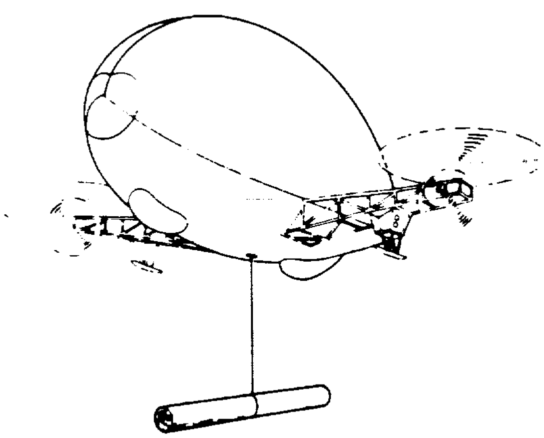


Fig. 3.5 Modern Helicostat

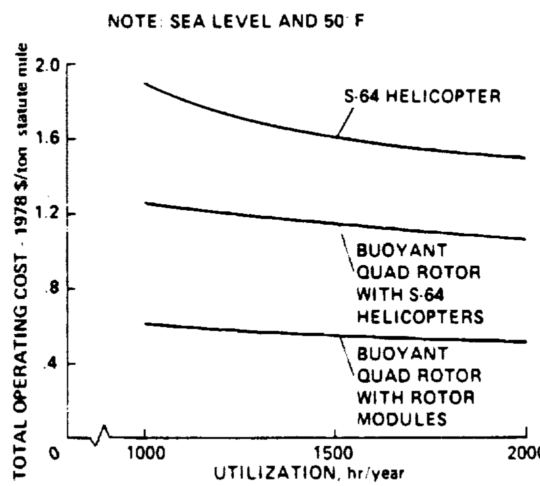


Fig. 3.6 Relative heavy-lift operating costs

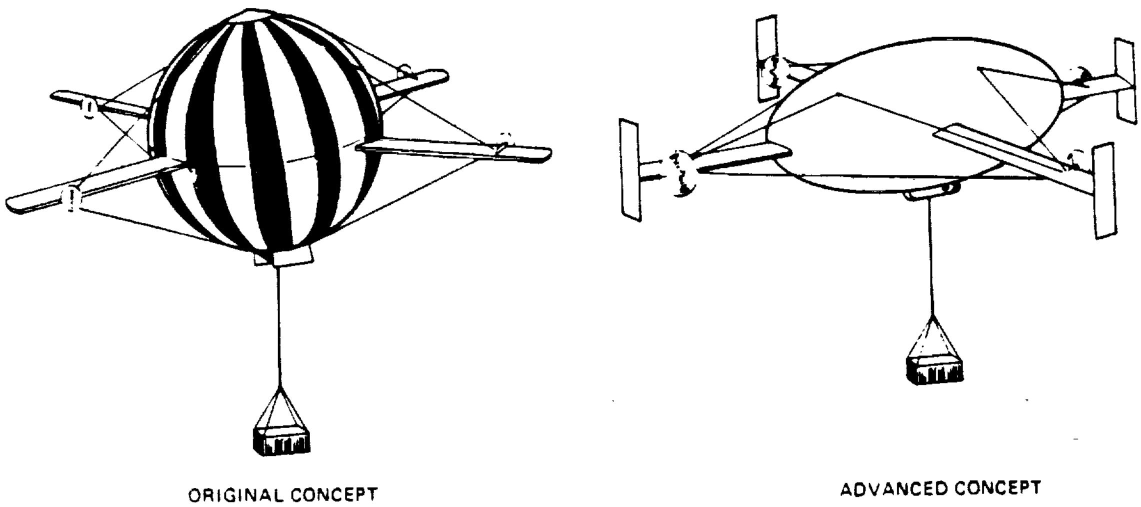


Fig. 3.2 Rotor-balloon (Aerocrane) concept

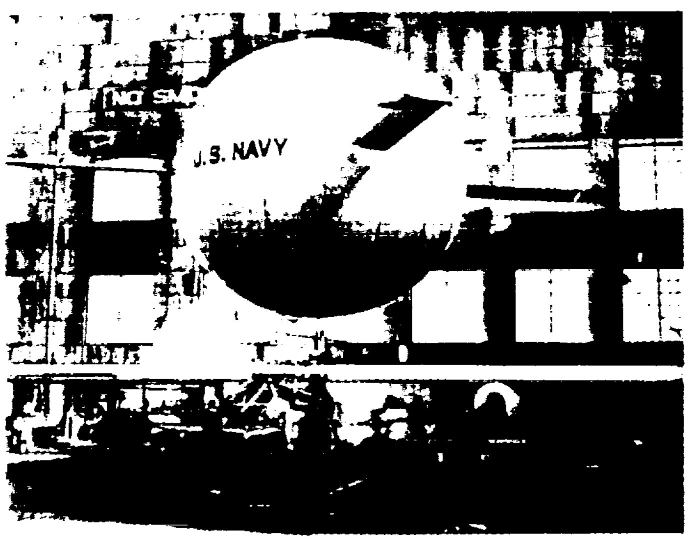


Fig. 3.3 Aerocrane remotely controlled flying model

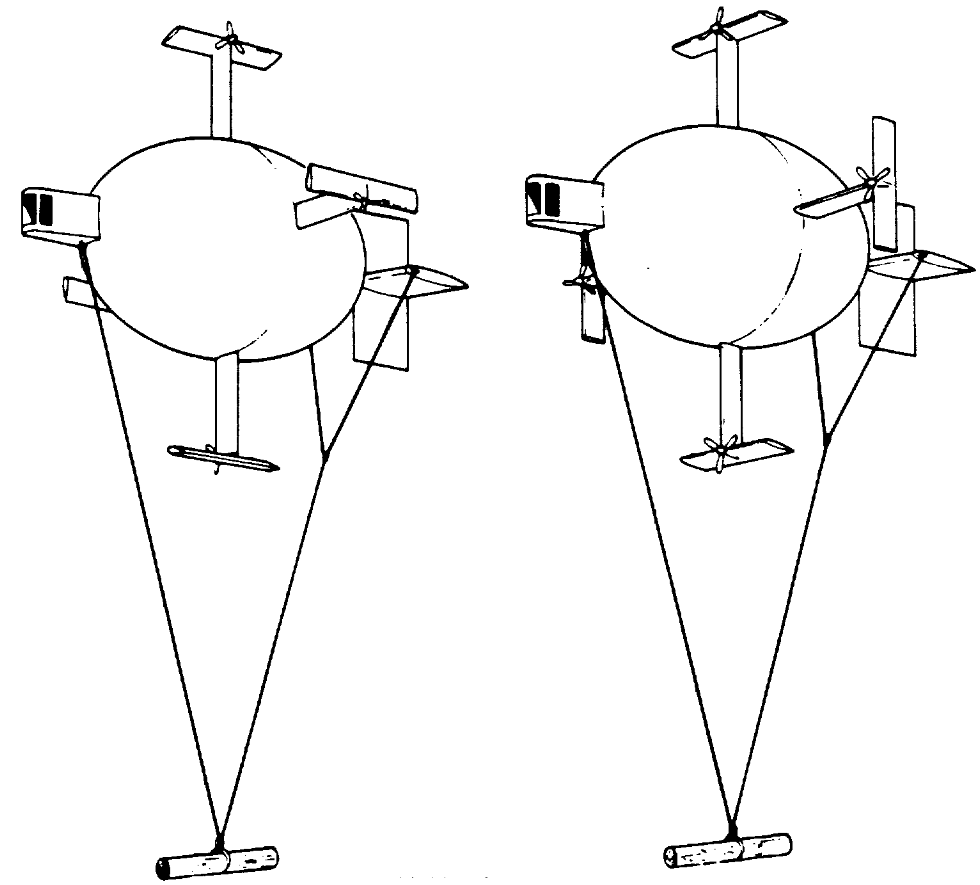


Fig. 3.9 Cyclo-Crane concept

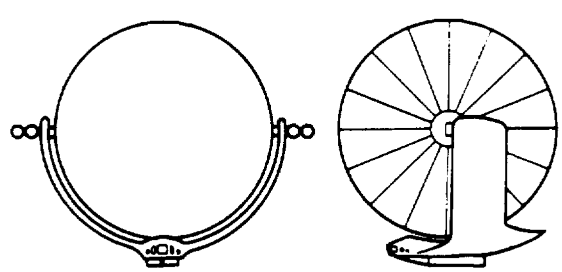


Fig. 3.10 Rotating sphere concept

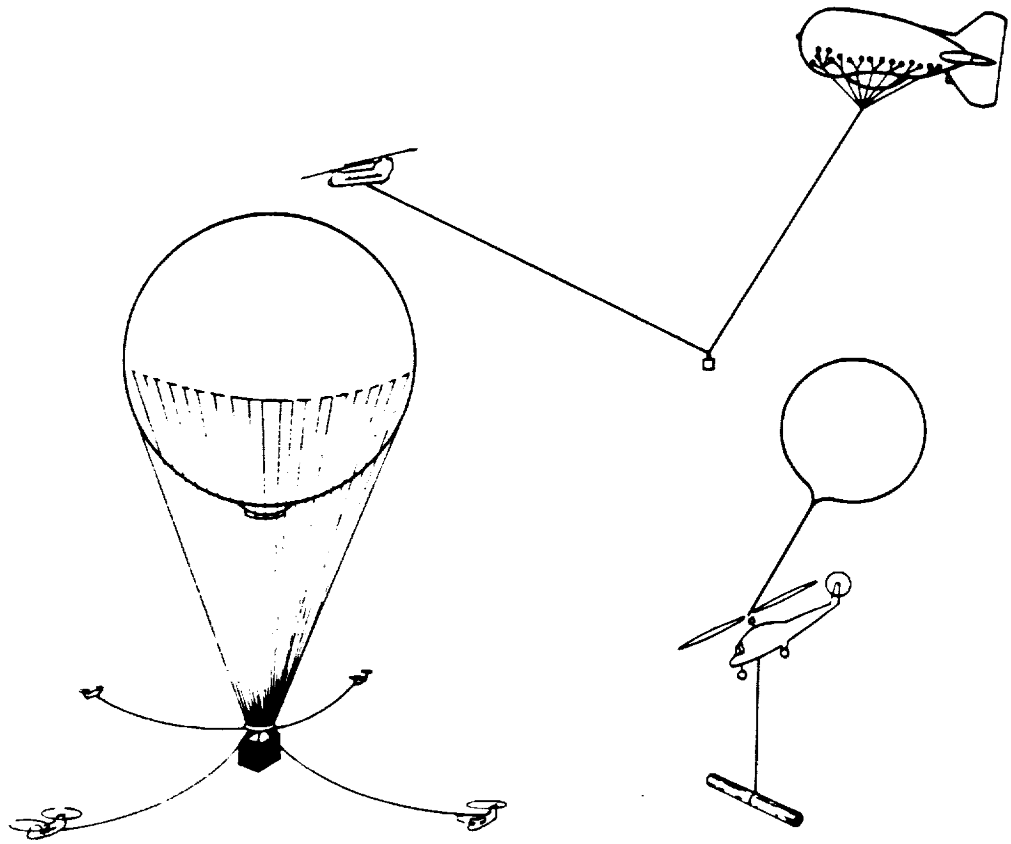


Fig. 3.11 Combined descrete concepts

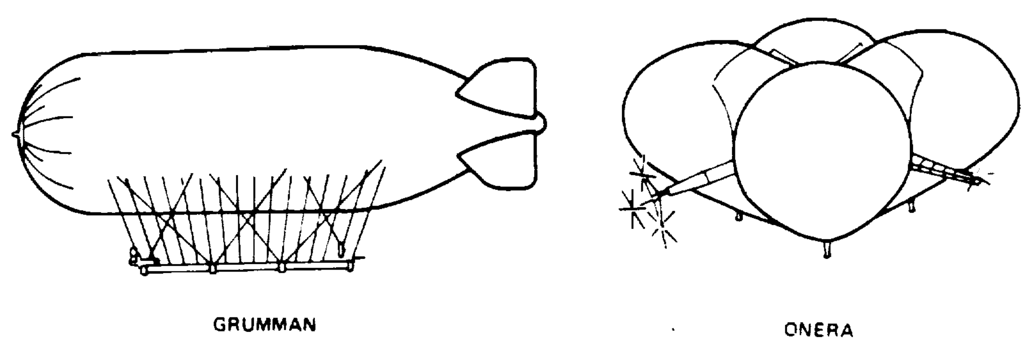


Fig. 3.12 Multielement concepts

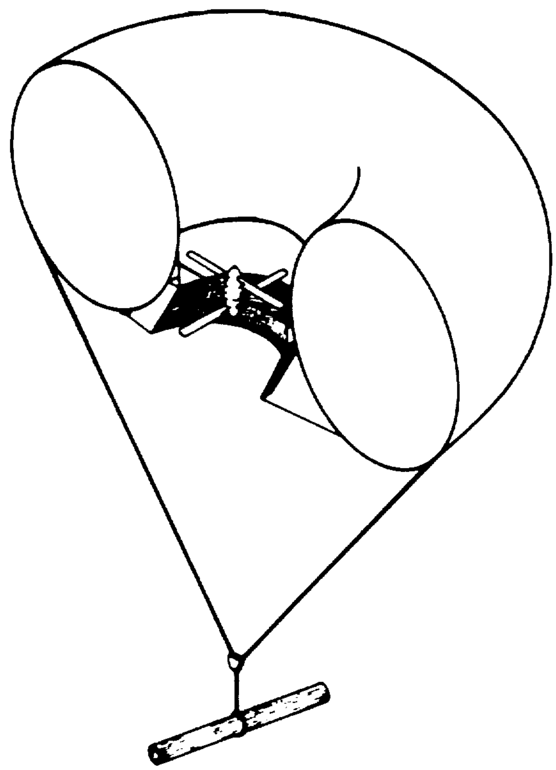


Fig. 3.13 Ducted-fan concept

4. HIGH ALTITUDE PLATFORMS by Norman Mayer, NASA Headquarters (Ret.)

4.1 Military and Civil Needs

The obvious benefits of aerial observations caused the balloon to be used as a military surveillance platform only 10 years after its conception and development by French experimenters in the 18th Century. Cables or lines between the balloon and ground anchor points were used to achieve fixed spatial locations. Improved more stable tethered balloons were developed later using cylindrical or ellipsoidal envelope forms equipped with air inflated tail surfaces. These types were used in World War I as manned observation platforms and in World War I and II as unmanned "barrage balloons" to discourage low altitude aerial attack. Tethered balloons continue to serve as sensor platforms and for other applications in military service. Civil versions are currently being used as telecommunications centers flying at 3000 m altitudes.

There are also important military and civil applications for platforms which can fly at altitudes beyond the capabilities and limitations of tethered systems. Since much success has been achieved with free flying stratospheric balloons, it has seemd reasonable that this technology could be applied to development of powered versions with station-keeping capability; namely, high altitude airships or dirigibles. Consequently, a number of developmental programs and studies have been addressed to achieving this objective. This section is a review of these efforts.

Two prime military needs continue to require improved observational or sensing techniques: (1) early evaluation of threat danger, and (2) location and neutralization of enemy forces. In modern times, these needs have driven sensing altitudes into the stratosphere and even beyond into space. Satellites and airplanes perform some of these required functions but are limited by payload capacity, location flexibility, and high cost (Ref. 4.1).

Sensing of over-the-horizon information is limited by current line-of-sight frequencies used in communications and in weapons guidance equipment. Therefore high altitudes extend sensing distances. Defense scenarios can involve months of observation time but also require ready deployment of an observation and communications platform at very particular locations. Thus both long endurance and relatively rapid deployment are important.

A high altitude platform at 21,000 m can extend a detection perimeter outward to a radius of 33 nautical miles (600 km) for surface threats and to 440 n. mi. (800 km) for aircraft flying at 3000 m. Since the platform can be located at the radius distance from the command and control center, the distances between the threat and the target are essentially doubled relative to existing aircraft. This provides more time for detection and interception (Ref. 4.2).

Turning to civil needs, a high altitude geo-stationary platform can provide many of the functions of synchronous satellites plus a host of other services at a fraction of the cost (Ref. 4.3). Continuous regional coverage without the radio path losses associated with space-based systems is possible. A further national advantage is the avoidance of the problem of frequency saturation and other international complications.

Civil telecommunications is the outstanding application for platforms and would include the following services: (1) Direct TV home telecast, (2) Remote area telecast, (3) Communications experiments, (4) Educational and medical information, and (5) Mobile telephone relay and personal receivers.

Other potential benefits have also been identified (Refs. 4.3, 4.4) such as: (1) Forest area surveillance, (2) Ice mapping, (3) Coastal surveillance of air and sea traffic, pollution monitoring and weather observation, and (4) Scientific experiments.

4.2 Vehicle Basic Requirements

Minimum expenditure of energy for station-keeping requires operation in minimum winds. All studies of platforms have assumed, therefore, that the operating altitudes would be in the stratonull region of the atmosphere. This is a zone of low winds, which varies in dimension and altitude depending on location and season. For airship design, a nominal pressure altitude of 50 mb. has been assumed which under standard conditions equates to a geometric altitude of approximately 20,700 m.

Detailed analyses of wind data show that design for a peak velocity of 50 knots would satisfy a 95 percentile probability for operations over most U.S. locations (Ref. 4.5), and design for 75 knots would be sufficient for most worldwide points of interest (Ref. 4.6).

The maintenance of flight at any altitude requires elimination of, or provision for, changes in static lift caused by atmospheric and radiation effects. The most important is the variation in superheat, which is the differential temperature between the lifting gas and the atmosphere. Low pressure scientific balloons on short endurance flights use a combination of gas venting (to control rise) or dropping ballast (to stop descent). Low altitude airships are able to use aerodynamic lift (positive or negative) while under way. This latter means is also available to high altitude platform types, and studies have shown that the magnitude of the compensating forces required do not exceed the capabilities of the airships to generate them (Ref. 4.7). However, flying the airship at some pitch angle may compromise its mission performance. A further disadvantage is the need for circling flight (to maintain station) when wind velocities are below the airspeed required for aerodynamic lift.

Another means of altitude control is the use of superpressure. This principle involves maintaining a constant volume of lifting gas while allowing the internal pressure to vary between that required for structural integrity and aerodynamic function and that produced by superheat effects. This principle is used in high pressure scientific balloons where long endurance and constant altitude is required and works well. It involves use of stronger, hence heavier, envelopes and therefore larger envelope volumes are required for equivalent payloads.

Vectored thrust could be considered where propellers or rotors are used to produce vertical thrust similar to the hybrid heavy-lift airships described in Section 3. These types would be heavier and have higher drag for a given payload and may also complicate the accommodation of payloads.

Other methods of controlled lift could include use of artificial superheat at night (derived from propulsive heat); that is, lifting gas could be compressed and stored in the daytime and released at night. Alternatively, compound gas systems, employing the ballasting effects of vapor-liquid gas states, could be used (Ref. 4.8).

Each approach has its advantages and limitations. The only one used for long endurance balloons thus far has been the superpressure principle. High altitude conditions allow consideration of concepts which would not be practical for low altitude airships, such as the gas compression principle which is limited to low rates of gas volume change.

At the 50 mb pressure altitude, the air density is only 0.06 that of sea level. This requires a 94 percent gas volume change between launch (or takeoff) and operating altitude. One method of accommodating this change is to launch the airship as a free balloon with a small bubble of helium in the top of its envelope. In this case, the airship must be flown initially with its major axis vertical and most of the envelope suspended in a flaccid condition. The ascent to altitude is a drifting flight and essentially uncontrolled. Launch is limited to the same conditions as those for balloons, namely low winds.

A second method requires the airship to be fully inflated (94% air) and launched like a conventional low altitude airship. Under these conditions, the vehicle can be flown to altitudes under control. A disadvantage is that of ground-handling a large airship in such manner as to avoid damaging the structure. This method offers some flexibility over the balloon launch technique but is also limited to times of very low winds on the ground.

The choice of design concepts involves the many interrelated factors usually associated with aircraft design; but for high altitude airships, which take about 17 m^3 of helium to lift 1 kg (at 50 mb), most design choices are heavily influenced by their effects on weight.

4.3 Early Projects and Studies

Some initial investigations utilized powered scientific balloons as platforms. Two experiments (HI-PLATFORM I and POBAL) were flown by the U.S. Air Force in the 1960's using natural shaped polyethylene balloons to support battery-powered propulsion modules. A later Air Force project involved a small solar powered airship (HI-PLATFORM II). This was flown at 20,420 m for a total of 2 hours (Ref. 4.9).

The first major effort toward long duration flight was a U.S. Navy sponsored program known as High Altitude Superpressure Powered Aerostat (HASPA). This program was designed to demonstrate station-keeping at 21,335 m while supporting a 90 kg payload for a flight duration of 30 days. An airship approach was used employing a modified class C envelope shape with a volume of 22,656 m^3. Constant altitude control was to be achieved using the superpressure principle. Propulsion was provided by electric motors driving a vectorable (for control) stern mounted propeller. Electric power was to be furnished from batteries, fuel cells, or solar cells. Launch was to be accomplished in the free balloon manner, and only the payload and power supply system were to be recovered. Two flights were attempted but none were successful due to materiel failures at launch. The program was subsequently terminated and replaced by HI-SPOT (Ref. 4.10). These early programs are summarized in Table 4.1.

The U.S. Navy Program, "High Altitude Surveillance Platform for Over the Horizon Targeting -- (HI-SPOT)," incorporates the major objectives of HASPA but also includes a mission scenario. The latter requirement involves launch from a U.S. base, flight at 19-22,000 m altitude over a distance of 6000 nautical miles to station-keeping location for a 19-day surveillance period (assuming 44.6 knot average winds) and carrying a 250-kg payload. Transit to and from the station assumes utilization of wind patterns so that power and fuel requirements are equivalent to flying a round trip of 1000 nautical miles in still air. These requirements have resulted in a vehicle design concept with a hull volume of 141,600 m^3, a maximum speed of 75 knots, and equipped with a 158 H.P. propulsion system (Figs. 4.1 and 4.2).

A key feature of the HI-SPOT concept is a low drag envelope. This design is based on the principle of maintaining a laminar flow boundary layer over the forward half of the hull. This is achieved by using a Carmichael' dolphin shape (Ref. 4.11), with its maximum diameter located at 50-60% of the hull length. Very smooth and accurate hull contours are also required and if these can be achieved, a total drag coefficient of 0.016 is expected.

The HI-SPOT would use a "4 layer" envelope material designed to minimize diurnal temperature effects. Power is provided by a hydrogen fueled internal combustion system driving a single gimballed propeller which is also used as the primary means of directional control. High metacentric stability is relied upon for longitudinal balance and augmented by trimming effects from ballonets and water ballast.

The HI-SPOT airship is intended to be launched and recovered as a constant volume hull; i.e., completely inflated at all times. Helium and air would be separated by two bulkheads and three ballonets for trim control during takeoff and climb. Once maximum altitude is achieved, a super-pressure mode could be used. Constant mass would be maintained by use of engine exhaust water recovery. It is planned to allow air to mix with helium on descent and use ballonets for trim (Ref. 4.12).

Initial studies of the concept have been completed. The next phase, if accomplished, would include scaled demonstration flights and some technology development.

The benefits projected for the use of high altitude powered platforms (HAPP) for telecommunications and other civil applications have been investigated in a series of studies by NASA which focused on missions, power supply systems, and vehicle concepts. All of these studies were based on the assumption of a geo-stationary vehicle operating at the 50-mb level over various sites in the U.S. It was also assumed that the airship would be launched and recovered at or near the locations over which it would fly, and essentially no transit would be required. These requirements allow serious consideration of the use of microwave energy projected from a ground station as a power source for propulsion and payload. On this basis the endurance of the airship is not limited by fuel supply, and very long time on station becomes a possibility (Ref. 4.13).

Several concepts have been considered in studies of the HAPP vehicle. A first approach assumed use of a conventional nonrigid-type hull equipped with ballonets and using dynamic lift to counteract static lift changes. Subsequently, hull shapes similar to the HI-SPOT have been identified as more desirable. The difference in requirements between the military and civil systems and the use of microwave power results in a much smaller airship. The HAPP would lift a 675-kg payload but would only need an envelope volume of 70,800 m^3 (Ref. 4.14).

4.4 Propulsion

At present, there are no existing propulsion systems which are readily applicable to high altitude platforms. Some near term configurations may be possible using existing components, such as photovoltaic units and electric motors; but in general, a technology development program is indicated for any operational applications. There are several basic power options for propulsion of high altitude platforms. These include: chemical, electro-chemical, electro-radio, electro-optical, nuclear, and solar-thermal. Some of these are compared in Fig. 4.3 which assumes a constant cruise requirement of 75 knots. The interrelationship between mission, vehicle, and power train requirements dictates the choice of a suitable system. For example, a vehicle which must cruise from base to a distant location, such as the HI-SPOT, is not able to use microwave power even though this is the most efficient system. Likewise, some of the other systems (solar cells) which do not change weight with duration are not applicable because the surface area requirements are excessive.

Other aspects which must be considered include minimum fuel consumption, high reliability, low heat generation and/or high heat rejection capability, minimum hazard effects (which tend to rule out nuclear systems) and low development risk and cost. As previously noted, high altitude airships are extremely sensitive to weight effects, so that minimum mass/thrust power ratio remains a most important criterion. These various factors were considered in current studies of military and civil vehicles and the propulsion systems were chosen accordingly.

The propulsion system for HI-SPOT has been projected as a liquid-cooled, turbocharged, reciprocating engine assembly driving a single 26 m dia. propeller and fueled with hydrogen. The engine assembly would consist of four four-cylinder powerplants each producing 39 kw of power. They would be coupled to the single propeller shaft through a 30:1 reduction gear. The hydrogen fuel would be stored in liquid form in spherical insulated tanks. Air would be delivered to the engines via a 20:1 turbocharger. The choice of this approach included, among other things, the state of technology development for the components involved.

The very high endurance of the HAPP vehicle and the non-transit aspect allowed a choice of the low mass/power ratio system available in microwaves. The transmittal of microwave power is also considered as a near term technology. This system involves generation of microwave frequency energy on the ground, beaming this energy to the aircraft using a suitable transmitting antenna, receiving the microwaves on the airship and converting them to DC electric power. A rectifying antenna on the airship accomplishes this latter function. The power density in the microwave transmission can be selected to enable practical size of antennas and rectennas to be used. A transmitting frequency of 2.45 GHZ was used in all studies since it is relatively insensitive to atmospheric attenuation, represents a current state of development, and is acceptable from a hazard standpoint.

If it is assumed that part, or perhaps all, of the envelope is transparent to microwave energy, the rectenna can be mounted within the gas or air space to obtain minimum drag.

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Project name	Agency	Type Vehicle	Contractor(s)	Flight Date	Status	Results
High Platform I	A.F.	3000 m^3 Free Balloon + Powered Gondola	Goodyear/ Winzen	9-68	Complete	Demonstrated initial feasibility at 21,335 m.
High Platform II	A.F.	1048 m^3 Airship	Raven	5-70	Complete	2 hr. flight at 20,420 m. Solar powered -- balloon launched.
High Platform III	A.F.	16,990 m^3	Raven	Study only	Complete	Study completed 8-71. Stern propelled -- solar powered concept.
POBAL	A.F.	20,136 m^3 Free Balloon + Powered Gondola	Goodyear	9-72	Complete	3 hr. flight at 18,287 m.
HASKV	A.F.	Airship	Raven	Study only	Completre	Completed 12-73. Defined requirements for utility vehicle. 90 kg payload.
POBAL-S	A.F.	28,320 m^3 Airship	Raven	Study only	Complete	Completed design 3-74. Fuel cell powered. 7 day duration -- 90 kg payload.
HASPA	Navy	22,656 m^3 Airship	Martin/ Sheldahl	Launch 3-76	Terminated	Failed on launch-- material & operational problems -- 90 kg payload.

Table 4.1 DOD high altitude platform projects

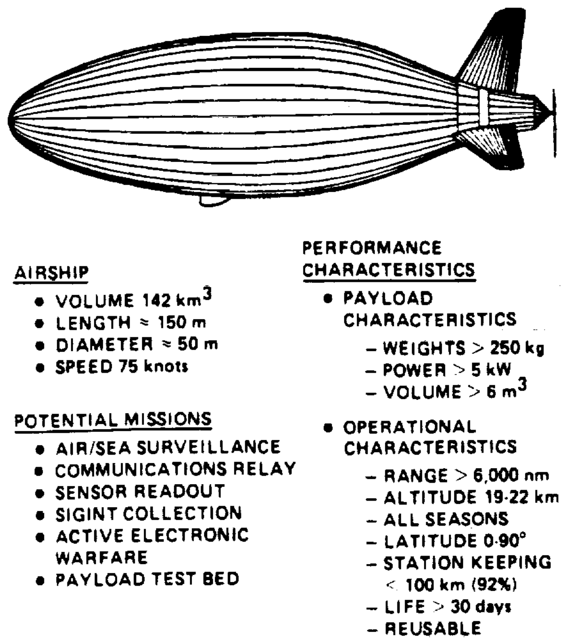

Fig. 4.1 High altitude surveillance platform for over-the-horizon targeting

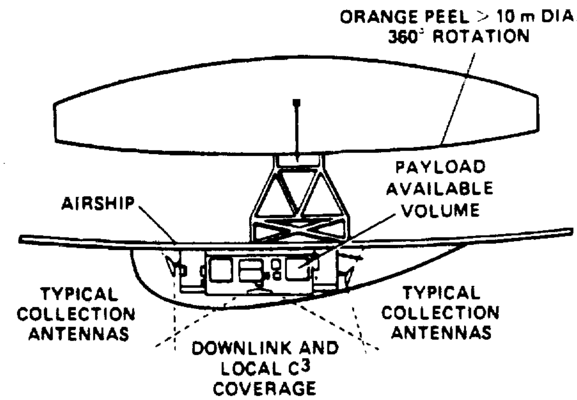

Fig. 4.2 Typical antenna installations

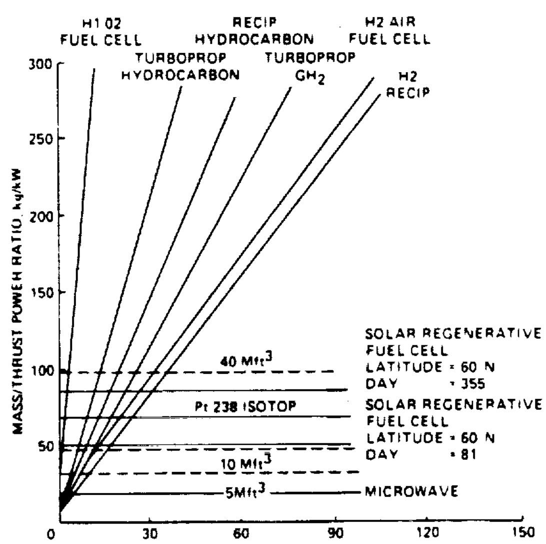

Fig. 4.3 Powertrain alternatives

5. TRANSPORTATION MISSIONS AND VEHICLE CONCEPTS

5.1 Background and Historical Trends

As mentioned in Section 1, one of the past uses of airships was commercial long-haul transportation by the Zeppelin Company. This mission has also received attention in many comprehensive studies of modern airships, such as the Feasibility Study of Modern Airships (Refs. 1.1-1.18), and has been the primary focus of many other assessments (Refs. 1.22, 1.23, 5.1-5.18). Our main goal in this section will be to analyze the potential of modern airships to compete in the transportation market.

The rapid growth of air transportation over the last 50 years has been due primarily to the economic gains resulting from the steady increase in the size and cruise speed of transport airplanes. Historically, productivity (cruise speed x payload weight) has been the most important parameter in long-haul transportation because higher productivity leads directly to higher revenues and lower operating costs per ton-mile. The economics of size are obvious, but the economies of speed are frequently misunderstood. High cruise speed is desirable for many reasons. First and most importantly, at least to the operators, higher speed means the hourly-based components of operating cost may be spread out over more miles and thus costs per mile will be lower.

A second advantage of a higher speed air vehicle is that it is less susceptible to weather delay than a slower one because headwinds will have less of an effect on ground speed, and adverse weather can be more easily avoided. Finally, there is the customer appeal of shorter trip times.

Recent increases in airplane speed have been possible because the flight efficiency of the jet transport airplane tends to increase with increasing speed, at least up to about Mach 0.8. Of course, it has taken a great deal of development to realize the high speeds and flight efficiencies of today's airplanes.

The effect that increasing productivity has had on transcontinental air fares is discussed in Ref. 1.22. In the early days of commercial airplane transportation, fares dropped rapidly until about the time of the introduction of the DC-3. Then, fares remained approximately constant for nearly 30 years. Thus the increasing productivity had the effect of nullifying inflationary effects for three decades, and air travel was a much better value in real terms in 1967 then it was in 1937. More recently, fares have tended to follow the general inflationary trend. This is primarily true because there have been no speed increases since 1958.

The effect of cruise speed on the flight efficiency of fully-buoyant airships is quite different from that of airplanes. The flight efficiency of fully-buoyant airships inevitably and rapidly decreases with increasing speed and no amount of development will significantly alter this trend. References 5.2 and 5.19 indicate that a modern airship with a cruise speed of 120 mph, or about one-fourth the speed of today's fanjet transport airplanes, will have the same flight efficiency and empty weight fraction as the airplane. Therefore, for equivalent sizes we may expect that such an airship will have only one-fourth the productivity of the airplane.

We conclude this subsection by directly comparing past commercial airship operations with airplane operations of the same era. There is no question that initially, until about 1930, airships were superior to airplanes for long-haul transportation in terms of performance, capacity, economics, and safety. However, neither form of air transportation was truly competitive with surface modes at that time.

In the 1930's the airplane surpassed the airship in terms of speed, operating cost, and even safety (Ref. 5.2). (It should be noted, however, that the limited operating experience, especially with large rigid airships, makes any statement of this type somewhat conjectural.) In 1937, the most advanced passenger airplane (DC-3) had double the cruising speed of the most advanced airship (the Hindenburg). References 1.3, 5.20 and 5.21 indicate that in 1937 the DC-3 had total operating costs per seat-mile between one-half and one-third those of the Hindenburg. Although the Hindenburg disaster and the approach of World War II hastened the end of commercial airship operations, it is clear that the fundamental cause was the growing inability of the airship to compete economically with the airplane in long-haul transportation.

5.2 Mission Analysis

Although past commercial airship operations have consisted primarily of long-haul transportation of passengers along with freight and mail, because of the airship's low speed and productivity this is not a likely mission for a modern airship. One passenger-carrying possibility is for a cruise ship type of operation but the market size for this application is likely too low for development incentive.

Because of an airship's natural attributes and drawbacks compared with other transportation modes, attention for passenger airships is drawn to short-haul applications. For short stage lengths, the speed disadvantage of airships as compared with airplanes is relatively unimportant. However, the V/STOL capability and the relatively low noise and fuel consumption (due to lower power levels) of the airship become important advantages. These advantages may allow an airship to penetrate short-haul markets which have to-date been unavailable to heavier-than-air craft.

In fact, there are passenger markets not presently serviced by the trunk or local airlines because of their short stage lengths or other factors. Specific missions are service between city centers, between minor airports, and airport feeder service. Vehicles in the 30- to 150-passenger range would be required, and stage lengths would lie between 20 and 200 miles. Air modes offer no advantages over ground modes at stage lengths less than about 20 miles and passenger airships probably cannot compete with airplanes at stage lengths greater than 200 miles. Presently existing competing modes include general aviation fixed and rotary wing aircraft as well as ground modes. Air modes have been able to cases they allow savings in door-to-door times. An airship has a good chance to be competitive because of the relatively high operating costs of the competing heavier-than-air craft. In fact, Airship Industries envisions the short-haul passenger market as one application of its AI-600 airship.

Turning now to the transportation of cargo, speed is not as significant to shippers as to passengers as is evidenced by the relatively low percentage of cargo that travels by air. For example, the air mode carries only 0.5% of the total cargo by weight in the U.S.-Europe market and less than 0.2% of the U.S. domestic freight. Because of the higher availability of trucks and their more numerous terminals, trucks generally give faster door-to-door service (as well as lower cost) than airplanes at stage lengths less than 500 miles. Because of the airship's low productivity, it is not likely it will be able to compete economically with either existing air or ground modes of cargo transportation. However, there may be a range of stage lengths centered around 500 miles for which an airship service could offer lower door-to-door trip times than any other mode could offer. Thus there may be a limited market for airship transportation of speed-sensitive, high-value cargo over moderate ranges.

In addition to the conventional cargo transportation missions just discussed, there may be special cargo missions for which the airship is uniquely suited. An example is transportation in less developed regions where ground mode infra-structure and air terminals do not exist (Refs. 5.22, 5.23). Agricultural commodities are a particularly attractive application since their transportation is one-time-only, or seasonal, in nature and crop locations are often in remote regions with difficult terrain. Closely related to this application is timber transportation in remote areas. The problem with this class of application is that the market size is not well-defined at present and may be too small to warrant a vehicle development. There is the same problem with long-haul transport of heavy and/or outsized cargo. Short haul of heavy cargo, on the other hand, appears to be a viable application and this mission was discussed in Section 3.

An airship application frequently mentioned a few years ago is the transportation of natural gas. This application is unique in the sense that the cargo itself would serve as the lifting gas and possibly even as the fuel. Significant advantages of an airship over pipeline and liquid-natural-gas tanker ships are increased route flexibility and decreased capital investment in facilities in countries which are potentially politically unstable. However, an early study (Ref. 1.7) found that, because of the extremely low costs of transportation by pipelines and tankers, airship costs would be several times higher than the transportation costs of existing systems. Thus, in spite of some obvious advantages, the transportation of natural gas does not seem to be a viable mission for airships.

For military long-haul missions, as opposed to civil missions, there are many important considerations other than operating cost. For example, vehicle requirements include extremely long range, very large payloads, low observable properties, and a high degree of self-sufficiency (minimum dependence on fixed ground facilities). Since an airship would compare very favorably with airplanes for many of these requirements, several authors have considered airships for the strategic airlift mission. Interest in this airship application stems not only from deficiencies in existing strategic aircraft but also from a severe capacity deficiency in the entire military airlift system. For example, the United States possesses about one-third of the airlift capacity that would be required in the event of a major NATO-Warsaw Pact conflict (Ref. 5.24). The question of how to provide the additional needed capability is obviously of vital importance.

Because of the limited amount of resources available for military forces and the global commitments of these forces, the United States and other western military powers have adopted a policy of limited forward deployment of forces. Strategic mobility is then required for reinforcement in the event of hostilities. In the early stages of a conflict, this reinforcement would be provided by conventional airlift. As sealift becomes effective (about 30 days for sealift between the United States and Europe), airlift would be used only for the resupply of high-value or critically needed supplies (Ref. 5.24). In this scenario, an airship could supplement the existing airlift and sealift capability by providing faster response time than sealift and greater payload-range performance than conventional airlift.

The advantage of an airship over an airplane for strategic mobility comes from the airship's characteristic of retaining its efficiency as vehicle size is increased (see Section 3.1). This allows consideration of vehicles with payloads several times those of existing transport airplanes. Figure 5.1, taken from Ref. 5.24, shows than an airship of 40×10^6 ft^3 volume could transport a payload of 300 tons from the middle of the continental United States to Europe and return (a distance of about 9000 nautical miles) without refueling. Thus fuel supplies at the offloading base would not be depleted. This capability is far in excess of what is possible with the C-5 airplane. The main question is whether or not such an increase in capability is affordable.

5.3 Vehicle Concepts

Both conventional and hybrid airship concepts have been proposed for transportation missions. We have previously discussed conventional airships and hybrid concepts for vertical heavy-lift. We now discuss hybrid airship concepts proposed primarily for transportation missions. These concepts include airships with wings, "lifting-body" shapes, multiple cylindrical hulls, and concepts which combine propeller/rotor systems with buoyant hulls. Both VTOL and STOL versions of these vehicles have been studied.

Early studies (Refs. 1.1-1.18) quickly eliminated both the more radical concepts (because of design uncertainty) and the multiple hull concepts (because of their relatively high surface area-to-volume ratios). More detailed analysis showed that winged airships are generally inferior to the lifting bodies. Therefore, the subsequent discussion will consider only lifting-body hybrids for long-haul missions and prop/rotor hybrids for short haul.

Many different lifting-body airship concepts were studied in Refs. 1.1-1.18. We will select the Aereon Dynairship (Ref. 5.14) as representative of this class of vehicle because of the background of information available on the delta planform lifting-body shape and because this vehicle has received the most attention.

The Aereon Dynairship (Fig. 5.2), consists of a buoyant hull of approximately delta planform with an aspect ratio in the range of 1.5 to 2.0. Control surfaces and propulsors are arrayed along the vehicle trailing edge for maximum efficiency. The Dynairship concept has received considerable analysis and development including the construction of a flight vehicle.

The basic idea of the Dynairship, as with all lifting-body hybrids, is to "flatten" the buoyant hull to obtain a shape with higher lift efficiency. On the negative side, this flattening increases the surface area which tends to increase friction drag and structural weight. There has been considerable disagreement in the literature as to the net effect of these trends. This question will be taken up in more detail in the following section.

A vehicle concept for the short-haul transportation mission, called the airport feeder vehicle, was studied in Refs. 1.15 and 1.16. The concept is a semibuoyant airship capable of transporting passengers or cargo to major conventional takeoff and landing hub terminals from suburban and downtown depots. The basic configuration and operational concept are depicted in Fig. 5.3. The hull is of the classical shape and is a pressurized metalclad construction of 428,500 ft^3. The vehicle gross weight is 67,500 lb; 35% of the total lift is provided by buoyant force with the remainder provided by dynamic forces. The propulsion system consists of four fully cross-shafted, tilting prop/rotors. At low speeds the propulsors are tilted to provide vertical lift and at cruise they are tilted to provide horizontal thrust, with the dynamic lift then provided by the hull being flown at a positive angle-of-attack. The design has an 80-passenger capacity and controllable VTOL capability. The cruise velocity for maximum specific productivity was estimated to be 130 knots at an altitude of 2000 ft. The noise level at takeoff was estimated to be 86.5 pNdB and the fuel consumption to be 0.25 gallons/ton mile. The major areas of technical uncertainty were identified to be the hover/transition phase stability, and the control characteristics and flying/ride qualities in turbulent air.

Turning to the military strategic airlift mission, a recent study (Ref. 5.25) has analyzed both conventional rigid and lifting-body hybrid airship designs for this application. It was found that both vehicle concepts had about the same performance, but the lifting-body design was judged superior due to the problem of ballasting for buoyancy control in conventional airships. The lifting-body airship proposed in Ref. 5.25 is shown in Fig. 5.4. It is a delta-planform configuration of low aspect ratio with a cylindrical forebody. Actually it is closer in appearance and performance characteristics to a classical airship than to the "high" aspect ratio delta-planform hybrids, such as the Aereon Dynairship. It can in fact be viewed as a conventional airship with a "faired-in" horizontal tail which is flown "heavy." The design features VTOL and hover capability, 115 knot cruise speed, and a payload of 363 tons. The configuration parameters were selected based on parametric study of this class of shape.

5.4 Productivity Analysis

In this section we take up in more detail the question of the productivity of modern airships. Specific productivity (cruise speed times payload weight, divided by empty weight) will be used as a figure of merit. Productivity is a vehicle's rate of doing useful work and is directly proportional to the rate of generation of revenue. Assuming vehicle cost to be proportional to empty weight, specific productivity is then a direct measure of return on investment.

Early studies have resulted in a wide variety of conclusions regarding the performance of airships in transportation missions. In particular, some studies have concluded that delta-planform hybrids have inferior productivity characteristics and operating economics when compared with classical, fully-buoyant, approximately ellipsoidal airships and that neither vehicle is competitive with transport airplanes. On the other hand, other studies have concluded that deltoids are greatly superior to ellipsoids and, in fact, are competitive with existing and anticipated airplanes. Reference 5.18 identified substantial differences in estimating aerodynamic performance and, most significantly, empty weight, as the cause of these discrepancies. This subsection is based on Ref. 5.18 and the results are in basic agreement with another similar study (Ref. 5.15).

In the parametric study of Ref. 5.18, four vehicle classes and two empty weight estimation formulas were analyzed for three standard missions. Specifically, the cases considered were (1) a classical, fully-buoyant, ellipsoidal airship whose weight is estimated by a "baseline" formula; (2) the same vehicle, but whose weight is estimated to be one-half that given by the baseline formula; (3) a conventionally-shaped airship flown with dynamic lift (and therefore a "hybrid"); (4) a "high" aspect ratio (1.74) delta-planform hybrid with baseline empty weight, similar to the Dynairship of Fig. 5.2; (5) the same vehicle with one-half the empty weight; and (6) a low aspect ratio (0.58) delta-planform hybrid similar to the vehicle shown in Fig. 5.4 with baseline weight. In all cases, it is assumed that ballast is collected to maintain constant gross weight during flight. Two empty weight estimation formulas are included because of the large discrepancies in this parameter in the literature.

The three missions are (1) a short range mission (300 n.mi. range, 2,000 ft. altitude, 100,000 lb. gross takeoff weight); (2) a transcontinental mission (2,000 n.mi. range, 13,000 ft. altitude, 500,000 lb. gross takeoff weight); and (3) an intercontinental mission (5,000 n.mi. range, 2,000 ft. altitude, 1,000,000 lb. gross takeoff weight). The six specific vehicles were optimized with respect to cruise speed and buoyancy ratio in terms of maximum specific productivity for each mission. The results of the analysis are shown in Fig. 5.5-5.7.

These figures indicate the following:

1. Empty-weight fraction has a relatively large effect on airship specific productivity. Reducing the empty weight by one-half and reoptimizing the vehicles results in higher best speeds and large increases in specific productivity (between 200% and 500%, depending on vehicle shape and mission).

Deltoids are more sensitive to empty weight than ellipsoids. (Because large, high-aspect-ratio deltoid hybrid airships have never before been designed, built, and flown, there is significant uncertainty regarding their structural weights.)

2. High-aspect-ratio deltoid hybrid airships have specific productivity comparable to that of fully-buoyant ellipsoidal airships, except at long ranges where fully-buoyant ellipsoidal vehicles are significantly superior.

3. Low-aspect-ratio (0.58) deltoid hybrid airships have higher specific productivity than fully-buoyant ellipsoidal vehicles, except at long ranges where they are comparable. Among the vehicle concepts considered, it is the best airship for all three missions, considered from a specific productivity standpoint. Such a vehicle seems to be an effective compromise between the good aerodynamic efficiency of the high-aspect-ratio deltoid and the good structural efficiency of the classical ellipsoidal airship. At longer ranges than those considered here, the classical airship would tend to be slightly superior.

4. For equivalent empty weight fractions, airships cannot compete with existing transport airplanes on a specific productivity basis. Values of airship specific productivity were approximately one-third, one-fifth, and one third those of equivalent size airplanes for the short range, transcontinental, and intercontinental missions, respectively.

5. The cruise speeds for maximum specific productivity of airships are very low compared with those of jet transport airplanes. This is particularly true for fully-buoyant airships at intermediate to long ranges for which optimum cruise speeds of 60 knots are typical.

The fuel efficiencies of fully-buoyant, ellipsoidal airships were found to be about five times better than those of transport airplanes. The fuel efficiencies of deltoid hybrid airships are intermediate between those of fully-buoyant ellipsoidal airships and airplanes, ranging from one and one-half to five times better than those for airplanes. Because airship fuel efficiency is highly sensitive to cruise speed, fuel efficiencies will be greatly reduced if higher speeds are adopted for operational reasons. In any event, airships will use less fuel than airplanes and will, therefore, become increasingly more competitive as fuel prices increase.

5.5 Economic Estimates

Direct operating cost (DOC) is the usual criterion by which a transportation vehicle is judged. Unfortunately, as is the case for productivity estimates, there has been also a great deal of disagreement between the various published estimates of airship DOC's. Some studies (Refs. 5.1, 5.3-5.5, 5.8) have concluded that airships are economically superior to transport airplanes, some (Refs. 5.6, 5.7, 5.9) have concluded they are about equal, and some (Refs. 1.22, 1.23, 5.20, 5.21, 5.26) have predicted that the DOC of a modern airship would be much greater than that of existing airplanes. These studies are critically reviewed in Ref. 1.22, where the discrepancies are found to result from differences in study ground rules and in differing degrees of optimism in technical and economic assumptions.

To compute the operating cost elements of depreciation and insurance, an estimate of vehicle unit acquisition cost is needed, and here already is a major cause of published disagreement. Although an accurate estimate of airship vehicle acquisition cost has yet to be made, Fig. 1.6 indicates the plausible conclusion that the development and manufacturing costs of airships will be roughly the same as those for airplanes and thus major capital investments will be required.

Table 5.1 compares an airship DOC as estimated in Ref. 1.22 with the DOC being experienced for the Boeing 747 (Refs. 5.26, 5.27). The airship is a 10×10^6 ft^3 modern rigid design; all costs are in 1975 U.S. dollars. The table shows that the airship has been assumed to have a lower unit cost and much higher annual utilization (due to its lower speed) but has only one-fifth the block speed of the 747. On an hourly basis, the airship has lower depreciation, insurance, maintenance costs, and much lower fuel costs. This results in an hourly cost for the airship which is about one-third that of the airplane. However, when converted to a per-mile basis, the airship DOC is about 2.4 times that of the airplane.

Assuming reasonable values of indirect operating costs, profit, and load factor, and using the DOC estimate just discussed, required airship revenues were also computed in Ref. 1.22. These revenues are compared to the national average revenues of several modes in 1975 (Ref. 5.28) in Figure 5.8. The figure shows that the revenue required for a profitable airship cargo operation is substantially greater than transport airplane revenues and many times greater than the revenues of surface modes.

When one considers short-haul VTOL airship operations, the economic competitiveness of airships improves considerably. This is because existing and anticipated heavier-than-air VTOL vehicles, mainly helicopters, are relatively expensive to operate as compared with conventional fixed-wing aircraft. An estimated breakdown of DOC for the airport feeder airship concept of Fig. 5.3 is shown in Table 5.2 (Ref. 1.15, 1.16). In comparison with other advanced, conceptual VTOL aircraft, the airship DOC of 5.52¢ per available-seat statute mile is economically competitive. In comparison with actual helicopter airline experience, it is superior by about a factor of two. The fuel consumption is estimated to be about 30% better than for current helicopters.

To conclude this section, all evidence points to the conclusion that airships will have difficulty competing with airplanes over established transportation routes. It will take a strong combination of several of the following requirements to make a transport airship viable: (1) large payload, (2) extremely long or very short range, (3) expensive or limited fuel, (4) low noise, (5) VTOL, (6) undeveloped infrastructure, and (7) high-value or critical cargo. The best possibilities therefore seem to be either a short-haul VTOL passenger vehicle or a large, long-range strategic military vehicle.

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	Airship Estimate	Boeing 747 Composite of Actual Data
Speed, mph	100	500
Payload, ton	100	125
Stage length, mi	2,000	2,000
Utilization, hr/yr	6,000	3,650
Unit cost, 10^6 \$	20	30
Depreciation, \$/hr	201	500
Fuel, \$/hr	135	1,200
Crew, \$/hr	500	500
Insurance, \$/hr	30	75
Maintenance, \$/hr	200	525
Total Direct Operating Cost, \$/hr	1,066	2,800
Direct Operating Cost, \$/available ton-mile	10.7	4.5

Table 5.1 Comparison of long-haul direct operating cost breakdowns

	Direct Operating Cost, cents/available seat statute mile
Depreciation	1.37
Crew	0.75
Fuel	1.25
Insurance	0.26
Maintenance	1.78
Helium Replenishment	0.11
Total Direct Operating Cost	5.52

Table 5.2 Airport feeder direct operating cost breakdown

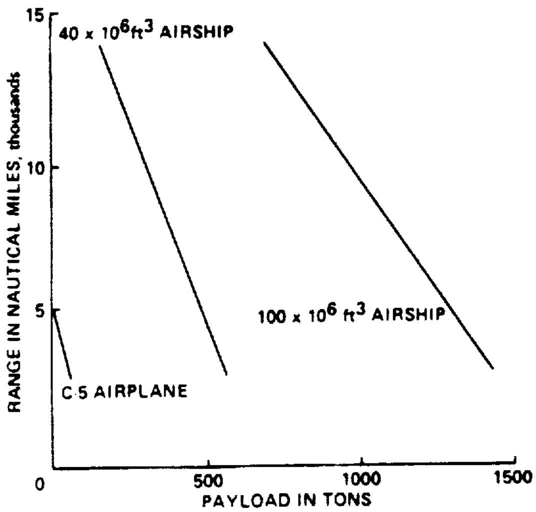

Fig. 5.1 Range/payload capabilities of large airships

Fig. 5.2 Aereon Dynairship lifting-body concept

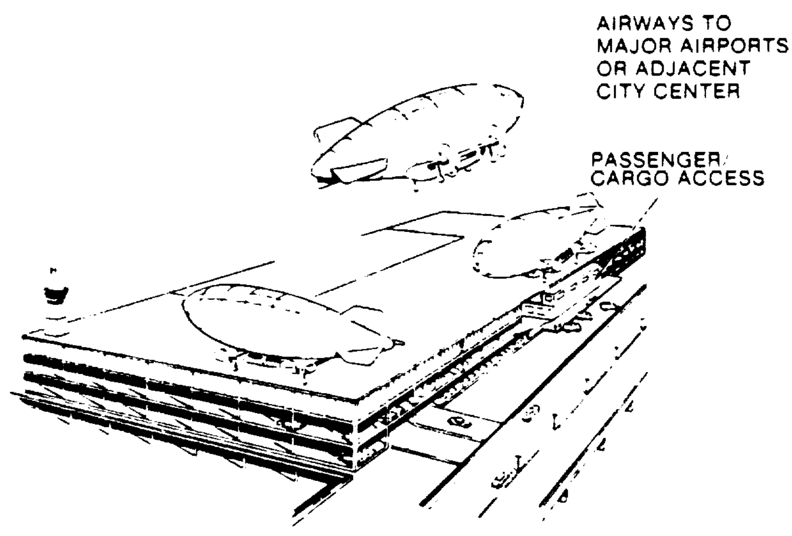

Fig. 5.3 Airport feeder concept

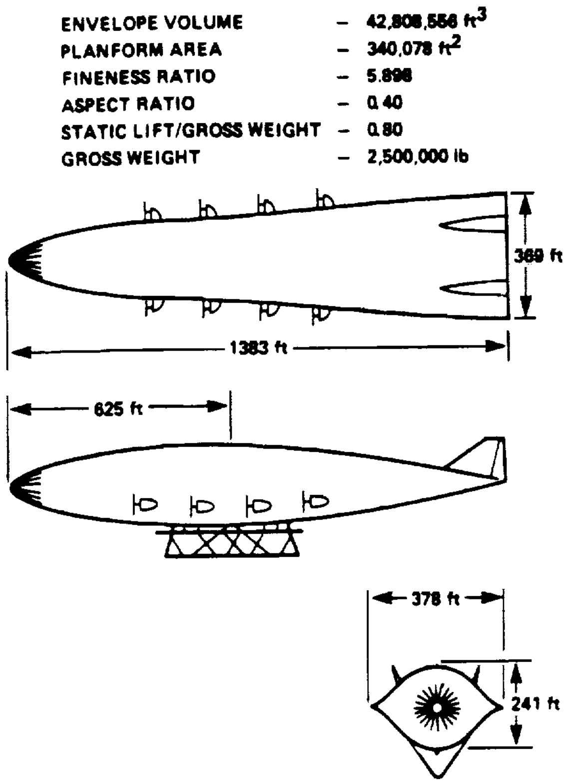

Fig. 5.4 Lifting-body hybrid strategic transport airship

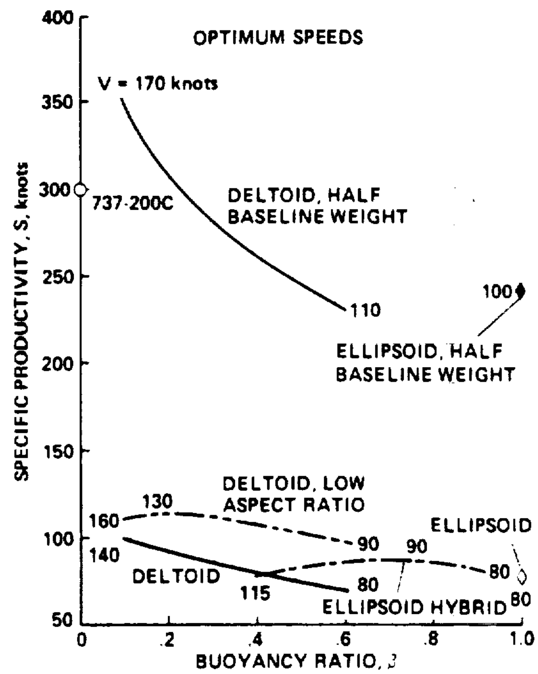

Fig. 5.5 Airship specific productivity, short-range mission

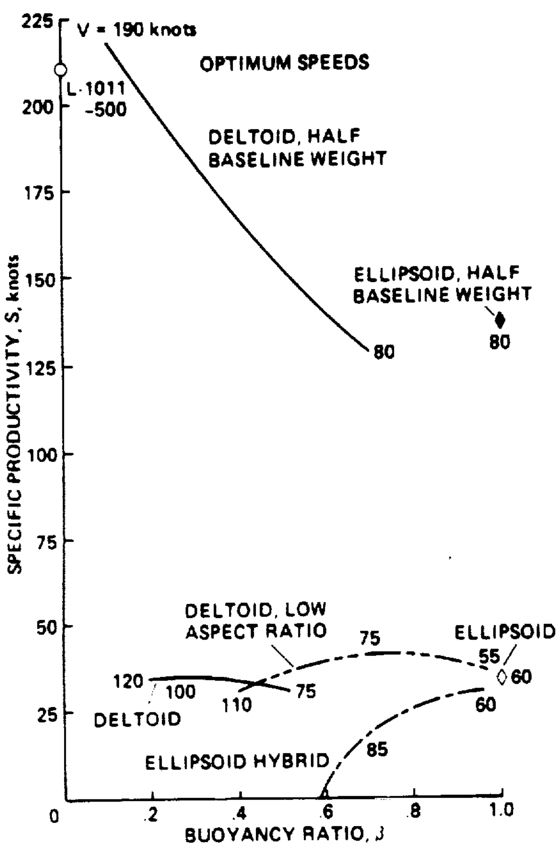

Fig. 5.6 Airship specific productivity, transcontinental mission

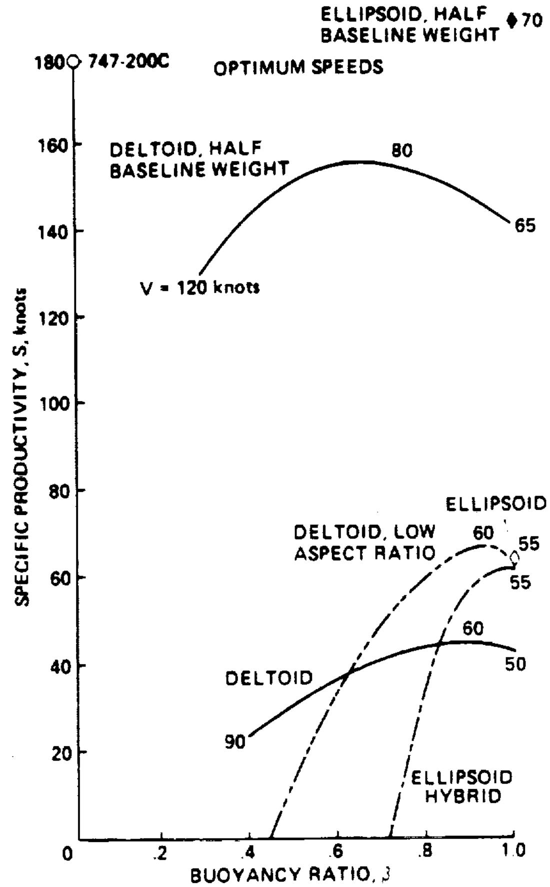

Fig. 5.7 Airship specific productivity, intercontinental mission

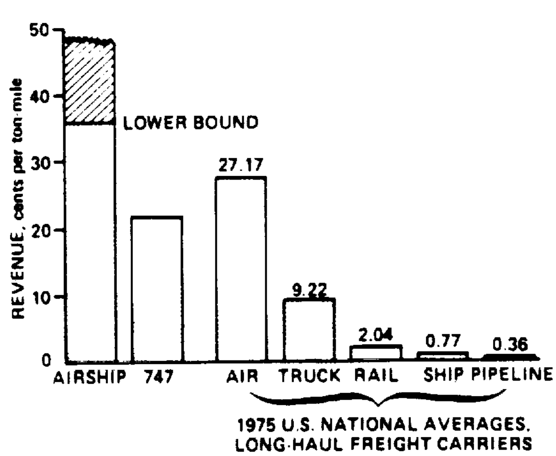

Fig. 5.8 Comparison of airship revenues with other modes

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16. Abstract

The primary purpose of this volume is to survey the results of studies, conducted over the last 15 years, to assess missions and vehicle concepts for modern, propelled, lighter-than-air vehicles (airships).

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